PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER

PEER DIRECTED STUDIES PROGRAM FOR REDUCING SEISMIC VULNERABILITY OF GAS AND ELECTRICAL DISTRIBUTION AND TRANSMISSION SYSTEMS

IGNITION OF FIRES FOLLOWING EARTHQUAKES ASSOCIATED WITH NATURAL GAS AND ELECTRIC DISTRIBUTION SYSTEMS

Robert Brady Williamson
and
Norman Groner
Department of Civil and Environmental Engineering

University of California
Berkeley, CA

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EXECUTIVE SUMMARY

The Pacific Earthquake Engineering Research Center (PEER) is conducting a research program on gas and electric utility lifeline systems. The key tasks of this research are the development and rapid application of advanced methods and technologies for reducing earthquake vulnerability and improving the system reliability and safety of natural gas and electrical distribution systems. This report describes the research project that was carried out to investigate the causes and impacts of fires following earthquakes. This effort takes a broad view of all possible causes of fires following earthquakes by using reported information from past earthquakes and sound reasoning to assess what caused the fires, including both ignition and fuel source. The gas and electric utility infrastructure and customer systems are investigated to determine to what degree they play a factor either as a source of ignition or as a fuel source. These results could help responsible parties to take appropriate action to reduce earthquake vulnerability and improve overall reliability and safety.

The first part of the report contains a survey of the literature describing fire ignitions during past earthquakes. Eleven 20th century earthquakes are reviewed. They are:

San Francisco, California	1906
Kanto (Tokyo) , Japan	1923
Hawkes Bay, New Zealand	1931
Long Beach, California	1933
Managua, Nicaragua	1972
Morgan Hill, California	1984
Mexico City, Mexico	1985
Whittier Narrows, Los Angeles, California	1987
Loma Prieta, California	1989
Northridge, California	1994
Hyogo-ken Nanbu (Kobe), Japan	1995

Based on these events, a list of ignition scenarios is developed in which the natural gas and/or the electric service play a role in the ignition of the first fuel in the fire, or as a fuel source. This report focuses on ignition scenarios associated with two types of residential structures. The first is one and two family housing (R-3 occupancies), and the second is multi-family residential buildings (R-1 occupancies). The scenarios identify the role that natural gas or electricity plays as a contributor to the original ignition and/or fueling of fires following earthquakes.

A systems approach for the analysis of post-earthquake fire safety is presented. The "Fire Safety Concepts Tree" or "Decision Tree" that was developed by the National Fire Protection Association (NFPA) on systems concepts for fire protection in structures is described. It is useful as a checklist for the analysis. It is essentially generalized goal decomposition intended to be applicable to any structural fire safety problem. It uses ends means logic to associate more abstract goals with more specific strategies for achieving those goals. The authors introduced two original systems, the Scenario-based Goal Decomposition (SGD) and the Influence Diagram. The SGD is described as an

intentional systems model to design and evaluate fire safety systems. It represents fire scenarios as a series of desirable system states that are driven by goals. The SGD approach defines fire safety goals as desirable states for a fire safety system. A schematic goal-decomposition model for utility-related earthquake fires is presented. This model is presented as an example of how goal decomposition can be used to link high-level objectives to the very specific strategies that can be used to accomplish them. The model is constructed to allow the calculation of probabilities associated with the prevention of ignition in a specific type of building. Influence diagrams show the dynamic relationships between events and/or systems states over time. A general model of fire ignition related to gas and electrical service during earthquakes is presented. The model can be modified and changed in many different ways as more details are added.

After a careful analysis, we concluded that the current stock of R-3 buildings in California does not pose a significant life-safety risk for post-earthquake fires. However, we also determined that there is some exposure for property loss. To address this exposure, we recommend that the proper reinforcement of hot water heaters and the awareness of earthquake preparedness in general should be fostered by utilities and other agencies. We believe it is the older multi-family residential buildings (R-1 occupancies) that are susceptible to structural damage and potential collapse, that represent the most likely places for people to be trapped during the initial hours of a major earthquake. Then before these people can be rescued, they become potential victims in the event of a fire. The improvement of structural integrity, appliance integrity, and the installation of seismically actuated shutoff valves or excess flow valves could ameliorate fire safety in these buildings. This includes appliance anchorage, flexible gas connection for appliances, gas and electric shutoff devices for homes and businesses, gas and electric distribution system shutdowns, improving the structural integrity of buildings, and finally public education and safety awareness in the earthquake aftermath. A discussion is given on the relative advantages and disadvantages of automatic earthquake actuated shutoff valves and excess flow shutoff valves.

Past earthquakes have shown that electrical power service will most likely be interrupted in the area affected by a very intense earthquake. Thus, except during a very short time after the initial shock of the earthquake, there are few ignitions caused by electrical shorts and arcs. The potential problems with electrical fire ignitions occur during the restoration of power. Before power is restored to an area, the electric utility needs to ensure that conditions are safe there. There should be an exchange of information between the emergency responders at the scene and the utility command center. Power should not be restored until services with damage have been isolated from the electrical supply.

A general review of a systems approach led to the important conclusion that in the post-earthquake environment, where fire fighting is likely to be severely restricted, attention must be paid to ignition prevention rather than fire management.

INTRODUCTION

The Pacific Earthquake Engineering Research Center (PEER) is conducting a research program on utility lifeline systems. Key research projects were identified that support development and rapid application of advanced methods and technologies for reducing earthquake vulnerability and improving the system reliability and safety of gas and electrical distribution systems. This report presents the research carried out to investigate the causes and impacts of fires following earthquakes. The objective was to take an interdisciplinary approach that will lead to methods to reduce the dangers of fires in the post-earthquake environment. The first phase of this project concentrated on ignition of fires following earthquakes with a primary emphasis on natural gas systems, while the second phase concentrated on the role of electric power systems with fire ignition. The research began with the identification of the causes of post-earthquake fires related to gas and electric distribution systems and customer facilities. Then various alternative means to reduce the safety threats posed by fires were evaluated. They included appliance anchorage, flexible gas connection for appliances, gas and electric shutoff devices for homes and businesses, gas and electric distribution system shutdowns, coordination of gas and electric service restorations, improving the structural integrity of buildings, and finally public education and safety awareness in the earthquake aftermath. Two systems approaches were used to describe the post-earthquake systems relationships, Scenario-based Goal Decomposition (SGD) and Influence Diagrams (ID). Both were found to be effective in evaluating the safety associated with these alternatives.

BACKGROUND

This report, reflecting the logical progression of our analysis, is organized as follows:

1. The literature describing fire ignitions during past earthquake events is described.
2. Based on that literature, a list of fire ignition scenarios is provided.
3. Systems analyses are described, based in part on the scenarios that would be expected to cause fires and resulting casualties. However, our analysis is not exclusively based on past earthquake events for three reasons:
   - Earthquakes are relatively rare, and their impacts are highly dependent on local factors. Therefore, generalizing from prior to anticipated events is difficult and highly speculative.
   - Earthquake events* inherently involve very high levels of variability; apart from the magnitude of the causative earthquake, many factors (e.g., the time of day and geographical location) will strongly affect outcomes.

* By earthquake "event" we mean the earthquake itself, the damage caused by the earthquake, and the human response to the earthquake.

- The effects of an earthquake event are influenced by the characteristics of utility systems, by the current utility operational practices, and by building types and occupancy characteristics, which differ from other areas that have experienced or will experience earthquakes.

Certain aspects of fire scenarios are not included in the detailed analysis because they do not involve gas and electric ignition or fueling aspects. Most notable among them is the risk of conflagration, which is largely a function of building construction and proximity as well as wind and humidity, regardless of the source of ignition.

The project started with a review of the causes of ignition of fires in recent earthquakes, and has focused on the injuries and damage caused by these fires. Fires after earthquakes occur in many different ways. Perhaps one of the most important challenges of this area of research is to take the lessons from past post-earthquake fires and apply them to reduce injuries and property damage in future earthquakes. An inventory of fire ignition scenarios was created that was quantified with the earthquake severity by either Peak Ground Acceleration (PGA) or Modified Mercalli Intensity (MMI) and with the source of energy such as natural gas, electricity, heating oil, coal, or cooking oil. The experiences of the Northridge and Kobe earthquakes were incorporated into this study. Of particular interest was A. Sekizawa's[48] discussion of the causes of fire ignition in the Kobe earthquake. He found that when one excludes unknown fire causes, most fires were derived from "gas leakage or gas apparatuses" and "other fire apparatuses or chemicals" rather than "electrical causes" for fires occurring shortly after the main shock. With elapsed time, the proportion of these fire causes decreased and the proportion of electrical causes increased and became the main source of ignition as the electrical service was restored.

It is important to take a broad view of each potential fire scenario and to include as many aspects of the system as possible. In addition, there are important human behavioral as well as organizational factors in both the home and commercial settings that can further complicate the situation.

It is also important to take a broad systems approach to identify post-earthquake fire scenarios, since future earthquakes may or may not experience some of the same elements that occurred in previous earthquakes. This is particularly important when the fire scenarios are the basis for investigating alternative means to reduce the threats posed by these scenarios.

System states are often used in the fire sciences to describe the growth and development of fires. Fire development progresses through a series of fairly discrete stages, or system states. Some models are based on an explicit description of how and when systems states change from one stage to another, and they are generally labeled as state-transition models. Stochastic models can be used to represent uncertainty in the transitions between system states[1,2]. Examples of models specific to fire growth include those developed by Beck[3] and by Ling and Williamson[4]. In general, the feasibility and value of such models have been well demonstrated when applied to the physical development of fire scenarios. Groner and Williamson[5] have demonstrated that system states can also be used to describe the manner in which human behavior affects the way that a fire incident develops.

We decided to base our analyses around the use of Desirable Systems States (DSS). A DSS is simply a way of describing a systems state that emergency planners or engineers hope to either preserve or establish. For example, a desirable system state might have the goal to prevent a fire from reaching flashover, or to limit the amount of natural gas available to fuel an unintentional post-earthquake fire. It is important to note that a desirable system state can be achieved or maintained through the actions of both hardware systems and/or people. For example, a sprinkler system activation might achieve the DSS of preventing flashover, or a person closing a door might achieve the same end. Groner and Williamson[6] have demonstrated that a fire incident, including both physical changes in the fire itself and the actions of active fire protection hardware and human behavior, can be modeled using DSS.

One can ask the question: "Why did you decide to base your analyses around the use of DSS?" The answer is that we wanted to make a positive goal as the objective of our analysis. It is feasible to also structure an analysis to prevent a given result or "undesirable" system state, but here the focus is on an unwanted results rather than on "success". It is far more acceptable to achieve a positive result than to prevent a bad result. It all boils down to the "glass is half full" is more positive than the "glass is half empty".

In this study, post-earthquake system states are described using two diagrammatic approaches: (1) "*Goal Decompositions*" and (2) "*Influence Diagrams.*" In both cases, system states are the nodes in the diagrams. Either approach can be quantified if and when it appears that it is worthwhile. The relationships among nodes (DSS) can be associated by probabilities that one system state will lead to another and by benefits and costs. For example, the costs associated with a desirable system state can be defined as the amount of resources that would be needed to change from an undesirable system state that will result without intervention to a desirable system state.

Causes of Post-Earthquake Fires Related to Gas and Electric Utility Service

As stated in the Background section, this project started with a review of the causes of ignition of fires in recent earthquakes, with a focus on the injuries and damage caused by these fires. In this section we will present comments from the literature on selected earthquakes, which will create an inventory of fire ignition scenarios. This section is patterned after Botting[7], who recently wrote a very interesting analysis of the impact of post-earthquake fires from the perspective of a fire safety engineer in New Zealand.

The goal of this section is to review the reports of past earthquakes, and summarize the fire scenarios that were directly related to the earthquake events. Fire safety analysis usually begins with the identification of fire scenarios[8], and once they are identified, the solution to the fire problem can be tailored to block one or more of the critical the "fire events"[#] that make up the fire scenario. This has been discussed above,

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[#] Every fire can be considered a "chain of fire events," and if the chain is broken the fire will stop or be limited in size but it is being restated here to bring attention to these aspects of the records of past earthquakes. A fire scenario is a generalized description of a possible fire incident that includes a description of the pre-fire conditions, the fire itself, and the subsequent behavior of people and the performance of fire protection devices. The use of fire scenarios can play an important part in improving building and fire codes.

At the end of this section, an "*Inventory of Post-earthquake Fire Scenarios*" is provided to identify the causes of post-earthquake fires related to gas and electric distribution systems and customer facilities. In addition, there is a discussion of the life safety and property damage impact of various post-earthquake fire scenarios.

San Francisco, California, Earthquake of 1906

The earthquake occurred at 5:12 am on April 18, 1906. The main shock had a reported "moment magnitude[§]" of 7.8 (Richter magnitude 8.3) and a maximum intensity of MMI IX in San Francisco. Scawthorn[9] estimated that the associated fires razed more than 12.2 sq km of the city, and destroyed at least 20,000 buildings. Scawthorn[10] also estimated that 50 outbreaks of fire were reported within the hour following the earthquake.

According to a 1985 EERI report[11], these 50 fires grew quickly to conflagration proportions because of lack of water. Steinbrugge[12] reported that the conflagration lasted 3 days, and caused substantially more damage than the earthquake. He noted that the original outbreaks of fire were in an area characterized by soft ground, which coincided with the predominance of building damage and of breaks in water, gas, and sewer pipes. Scawthorn et al.[13] described the post-earthquake fire problem as typically complex, involving many diverse elements as follows:

1. The earthquake caused structural and non-structural damage to buildings. The structural damage resulted in loss of integrity of many of the "passive"[**] fire-safety elements of buildings. In a similar fashion, there was a loss of serviceability of "active" fire protection systems such as automatic fire alarm systems, and sprinkler systems.
2. The earthquake caused damage to the infrastructure and to urban lifelines including water supplies, gas and electrical supplies, transportation systems, and communications networks (delays in reporting fires to the fire service allowed them to grow rapidly, escalating the demands on fire response).

[§] The seismic moment of an earthquake is a measure of the size of the earthquake that is related to the leverages of forces (couples) across the area of the fault slip. It is equal to the rigidity of the rock times the area of faulting times the amount of slip. Dimensions are in dyne-cm (or Newton-meters). The "moment magnitude" of an earthquake is estimated by using the seismic moment. (from Bolt, B., ***Earthquakes***, 4th ed., W. H. Freeman, New York, 1999, 340 p.

[**] Examples of "passive" fire protection components are fire resistant walls, floor/ceiling assemblies, and doors as well as the fire resistant coating, (often called "fire-proofing"), which are covering the structural components of a building. The word passive is used to distinguish these building elements from "active" fire protection elements such as sprinklers or heat and smoke vents.

3. Fires broke out initially and then spread before fire fighting teams had arrived. The severity of these fires depended on building density, the nature of the fire load*, and climatic conditions (wind and humidity).
4. Fire-fighting teams had to respond to multi-skill demands (fight fires, attend to other emergencies such as chemical spills and building collapses), and had impairment of water supplies, communications, and road access. This resulted in not all fires being responded to, and some fires spreading. The final result was that there were many small fires and a few that led to the conflagration.

One of the fire causes reported by Steinbrugge[14] was the breaking of internal electrical wiring as the result of structural damage to buildings, and since the electrical service current was not shut off for some minutes after the initial shock, this started fires. Other sources of fire were attributed to: the arcing of 550 volt tram wires with other wires, the consequent sparking and arcing of working electrical appliances and circuits in buildings, the collapse of buildings with fires in open fire places, lit kerosene lamps and gas lights in dwellings and businesses, and boiler fires in factories.

Steinbrugge[15] analyzed the mechanisms for fire spread, and identified three major elements for why the conflagration occurred:

1. Fire load per unit area was high,
2. Many fire houses and other fire-fighting facilities were damaged, and
3. Adversity of climatic conditions (there was a persistent wind and absence of rain).

In early 1906, San Francisco contained more than 90% wood frame buildings, also true today in many of its neighborhoods. Many of these wood frame buildings were four or five stories high, and they collapsed across streets. This was particularly common in residential neighborhoods.

During the early hours of the day of the earthquake, the wind was generally light, and from the west. It carried the fire into an area of low, spread-out blocks bounded by the Bay. Some water could be obtained, and some fires were brought under control. But as wind changes were occurring, the conflagration changed its direction of travel and systematically maximized the devastation. A major firebreak along Van Ness Avenue was regarded as one of the principal approaches to preventing spread to the west. If one goes to the neighborhoods west of Van Ness Avenue today, there are many wood-frame apartment houses and commercial buildings that are quite large and up to five stories in height. Many of these survived the 1906 earthquake as well as the fire.

The Kanto, Japan, Earthquake of 1923

This earthquake occurred at 11:58 am on September 1, 1923, and the main shock had a moment magnitude of 7.8 (Richter magnitude 8.3). Steinbrugge[16] reported that over 100,000 lives were lost in Tokyo and its environs. There were 277 outbreaks of fire in Tokyo, and 133 of these spread. He also reported that fire damage was far in excess of direct earthquake damage, and that post-earthquake fires were uncontrolled and burnt large areas for days. Fires that burned for nearly 40 hours destroyed about 40% of

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* Fire load is the combustible content per unit floor area

Tokyo's structures. The earthquake and subsequent fires also destroyed 90% of Yokohama.

Botting[17] references a New Zealand study by Kenna who recounted that 53 initial outbreaks of fire were reported within a few minutes of the earthquake. He also reported that there were a total of 134 initial outbreaks, of which over 100 were of miscellaneous nature, and 30 were chemical fires. In Tokyo, fires burned 38 km^2 and destroyed 450,000 houses.

Kenna classified primary outbreaks as follows:

1. Direct contact between combustibles and open fire or hot materials as result of
   - a. dislodgment of heat source
   - b. dislodgment of materials falling onto heat source
   - c. fracturing of heat source container
2. Overturning of heat sources (stoves, kerosene lamps, heaters, cookers
3. Electrical short-circuits as a result of movement of defective wiring and dislodgment of supports between circuits normally separated
4. Burst fuel tanks

5 Rupture of gas and oil supply lines (Botting's summary does not say what proportion of the gas lines were inside buildings as compared with the distribution system outside of buildings).

6 Chemical fires started by liquids and vapors from broken containers

7 Fires intentionally started

8 Freak fires (presumably unexplained or of unknown origin).

Expert reviewers of this earthquake have generally concluded that the Japanese construction and contents of buildings seriously affected the ignition and spread of fire following this earthquake. In addition, the wind speeds were in excess of 25 mph for more than two days. Some of these winds may have been induced by the size of the conflagration.

Hawkes Bay, New Zealand, Earthquake of 1931

This earthquake took place on February 3, 1931 at 10:48 am. According to Kenna[18], the main shock lasted at least one minute and had a moment magnitude of 7.75(Richter magnitude 7.8). It was followed by many severe aftershocks during the weeks following the main event.

There were three primary outbreaks of fire that occurred almost immediately after the earthquake and they were in chemists' shops. Fire spread to a fourth building, a hotel, and it was fully expected that these fires would be contained. But just before noon a brisk easterly wind blew up, and before many minutes, the fire was raging throughout the whole of the central business district. The change of wind direction drove the fire from the chemists' shops to adjoining buildings, and from there the fire spread through the central business section. Moreover, the conditions were favorable for fire spread since the day of the earthquake was hot and dry and followed a dry spell of weather.

After an inquest, it was determined that fires that had originated in the chemists' shops were caused by conditions following the earthquake including the following:

1. damaged buildings
2. scattered wares. Bottles containing inflammable and highly volatile liquids were broken and released fluids and vapors that were readily ignitable by the Bunsen lamps used in the chemists' shops.
3. broken light, heat, and power distribution systems inside and outside buildings.

Long Beach, California, Earthquake of 1933

This earthquake happened at 5:54 p.m. on March 10, 1933. The main shock had a moment magnitude of 6.3 (Richter magnitude 6.3) and a maximum intensity of MMI IX.

Kenna[19] reported that this earthquake occurred while many evening meals were being prepared, and estimated 35,000 gas flames were burning, but the gas supply utility lessened the chance of conflagration through quick cutoffs at gas supply points. According to Kenna[20], the primary fire hazard can be reduced by rapid shutting off of gas and electricity supplies either by a pre-arranged disaster procedure or by automatic cut-off valves actuated by seismic shock.

Managua, Nicaragua, Earthquakes of 1972

Three earthquakes occurred between 12:30 am and 1:20 am on December 23, 1972 of magnitude M_8.5 5 to 6.5. Duration of the main shock was 5-10 seconds. The greatest damage occurred in the downtown area, which exhibited intensities of up to MMI IX

According to the EERI proceedings[21], fires broke out in four or five places within a very short time of the earthquake. Fire department resources were overwhelmed, as much of their equipment was buried in fallen buildings. Fires developed into a conflagration and raged virtually uncontrolled for three days. The fire was finally stopped on December 27 by a firebreak and continued firefighting. Steinbrugge reported from personal observations that fires were still burning ten days after shock

According to Kenna[22], the hazard of fire spread in two modern high-rise buildings, where several hundred occupants might have been trapped by fire in the higher floors, could have been a possibility had it not been for the time of day that the earthquake struck. Had fire occurred immediately after the earthquake, and had the shock taken place during working hours, life loss would have been substantial because of the debris-littered stairwells, jammed doors, and inoperative elevators. Fires on any floor would have spread rapidly from floor to floor through shattered fire-resistive enclosures, and around stairs and elevator shafts. Fire suppression and rescue efforts would have been very difficult.

The EERI Proceedings[23] stressed the importance of the impact of building damage on fire safety in multi-story buildings. After this earthquake, many stairways were partially or wholly blocked due to jammed doors and debris. When debris and smoke block stairways, and elevators are out of operation, critical emergency egress and fire-fighting response problems arise. These problems are compounded at night due to electrical power failure and lack of emergency lighting.

Morgan Hill, California, Earthquake of 1984

The moment magnitude of this earthquake was 6.2 with 5 to 10 seconds of strong shaking. The maximum intensity was MMI VII at Morgan Hill. According to Schiff[24], post-earthquake fire was the primary cause of damage in Morgan Hill and San Jose

Scawthorn et al.[25]reported that the causes of two major structural fires were broken natural gas pipes to heating elements in gas appliances, a water heater and a gas heater. Scawthorn[26] also reported that several residential fires were due to chimney and gas heater flue damage. One of the fires occurred when the gas service had been restored one hour prior to the fire.

According to Scawthorn[27], several fires were ignited by electricity.

1. There was an attic fire in a commercial laundry where electrical shorting in steel conduit caused a hot spot and the ignition of cotton lint in contact with it.
2. A snapped power line fell onto a dwelling roof, arced through the metallic roof covering, and ignited wooden structural members and house contents.
3. A floodlight fell onto the roof of a residence at the time of earthquake. It was turned on automatically by a timer device and the light overheated and ignited the roof covering.
4. There were three grass fires caused by arcing of fallen wires

Scawthorn[28] reported residents of the Jackson Oaks area were effective in preventing ignition when they turned off about 30% of their gas service, and the Fire Department completed the cut-off of all gas and electricity.

Mexico City, Mexico, Earthquake of 1985

The epicenter of this earthquake was in Michoacán, Mexico, and the event had a moment magnitude of 7.9[+] (Richter Scale 8.1), and 60 seconds of severe shaking. Although Mexico City was at a large distance from the epicenter, some of the worst damage occurred there. In the worst hit area, the intensity was MMI IX. According to Earthquake Spectra[29], this earthquake was exceptional in that it led to the largest toll of collapsed buildings produced by a single event in the country, and it was one of the largest experienced by a modern city built in accordance with advanced seismic design provisions. Bolt[30] reports that there were 9,500 deaths and 30,000 injuries

Botting[31] references a New Zealand Reconnaissance Team report identified in his paper as NZNSEE (1988). This report noted that Mexico City did not have a network gas supply system. Instead, tankers supplied LPG to storage tanks, commonly seen on building roofs. The NZNSEE (1988) study noted the following items about the post-earthquake fires:

1. Within 24 hours following the earthquake, about 200 fires were reported.
2. There was no major conflagration, presumably due to the type of construction, i.e. the absence of wooden buildings, and the absence of buried gas pipelines.
3. The fires played no part in the structural damage, but they probably killed trapped people who otherwise might have been saved.

[+] Bolt, Bruce, Earthquakes, 4th Ed., W. H. Freeman, NY. 1999, p. 295.

4. The only serious fire was due to a leak in the gas storage tank of the St. Regis Hotel, and the fire spread to an adjacent department store and office building.

The New Zealand team noted that although the earthquake occurred at about breakfast time for many people, there were no reports of cooking fires.

Bertero[32] reported that he had arrived in Mexico City early enough to see a fire in the St. Regis Hotel, and he believes that the fire had prevented the rescue of some people trapped in the building. As far as we could determine, the toll of persons lost in that fire has not been documented.

Whittier Narrows, Los Angeles, California, Earthquake of 1987

This earthquake occurred at 7:42 am on October 1, 1987, with a moment magnitude of 6.0 (Richter magnitude 5.7) with a major aftershock of 5.5 at 3.59 am on October 4.

It was reported in Earthquake Spectra[33] that the overall performance of the electrical distribution system, as measured by customer service disruptions, was good, although power was lost to about 37,000 customers that was due to a transformer fire fueled by an oil leak. In Los Angeles County there were numerous disruptions due mostly to burned-down systems, and entanglement of electric lines.

The same article in Earthquake Spectra reported about 1,400 gas leaks of which 75% were due to leaks from water heater appliance connections. Public service announcements right after the earthquake advised people to shut gas off to their homes; however the number of responses was not reported.

Smoke[34] reported that during first 5 hours after the earthquake, the LA Fire Department responded to 75 gas fires and 38 other structure fires, but no large-scale fires occurred. Approximately 5 hours after the earthquake, there were no new outbreaks of fires, and most of the fires that had occurred were extinguished.

The article in Earthquake Spectra[35] reported that there were only 20 earthquake-related structure fires within the LA County Fire Department area, with 10 of these in the Whittier area. The causes of the fires were reported as follows:

1. Arcing and shorting when power was restored to damaged electrical appliances or fallen light fixtures,
2. Combustible material moved towards a heater by earthquake motion,
3. Mixing of spilled chemicals, and
4. Burned down power lines

The same article further reported that a significant number of gas leaks were associated with the motion of water heaters, but it did not identify them as a cause of fire.

LOMA PRIETA, CALIFORNIA, EARTHQUAKE OF 1989

This earthquake occurred on October 17, 1989, at 5:04 p.m. as a result of a slippage of some 40 km of the San Andreas fault producing an estimated average surface wave moment magnitude of 7.0 (Richter magnitude 7.1)[36]. Its epicenter was located in the Santa Cruz Mountains, 16 km north-east of Santa Cruz, and 30 km south of San Jose. The toll was reported as 62 deaths, nearly 3,800 injured, in excess of 7,500 homeless, and property damages of 5.6 billion dollars. The MMI for San Francisco was typically VI, but in San Francisco's hardest hit area, the Marina district, the MMI was reported as IX and with ground motion amplification with intensity estimations of as much as 0.35 g's. There were heavy structural damages in this area, and, in addition, a fire destroyed one block of buildings. According to Coleman[37], there were 27 structural fires in San Francisco during the first seven hours after the earthquake. In all there were 41 fires reported in San Francisco[38]. The most serious fire started in a 4-story wood frame building containing 21 apartments, and a parking garage on the ground floor in the Marina district. The two lower floors of the building collapsed during the earthquake, but the cause of ignition of this fire is uncertain, though it was not believed to be from natural gas since the gas distribution pipes in the streets were extensively damaged. Fire fighters arrived at approximately 5:45 p.m., and found that there was no water pressure in the hydrant in front of the building. Shortly thereafter, an explosion shook the building and several other buildings were ignited. Water was found and relayed from a more distant hydrant but more explosions occurred destroying a number of hose sections. At 6:00 p.m. a fireboat and 3 hose tenders arrived. The water from the boat had positive effects and the fire was controlled by 8:00 p.m. Most of the 41 fires reported (33 out of 41) were at sites on unconsolidated soil, 5 on mud and fill, and the rest on stable bedrock. According to Alyasin and Bak [39], the low number of fires for an earthquake of this magnitude was due to the following factors: nearly zero wind speed, the relatively short duration of the earthquake, about 40 seconds, and well managed fire fighting efforts. In addition, according to Lew[40] the shutdown of electric power eliminated this as an ignition source, and caused electricity-powered safety valves to close, shutting off the pilot and interrupting the flow of gas at that point. Also the caution exercised by citizens was effective in preventing ignition of leaking gas.

Fires in other areas were also reported. In Berkeley an auto-body shop building was completely destroyed by fire, but the fire was contained to the building of origin. It was believed to have started when flammable liquids were spilled during the earthquake. Santa Cruz County had 20 fires. In the city of Santa Cruz, only one residential structure was destroyed by fire. The cause of this fire was reported as a main gas leak. A wildland fire erupted at Niesene Marks State Park, and in Watsonville, one single-family dwelling and two mobile homes were destroyed by fire. In Santa Clara County, a residential fire was due to a ruptured propane tank.

Northridge, California, Earthquake of 1994

This earthquake occurred at 4:31 am, Monday January 17, 1994, with a moment magnitude of 6.9 (Richter magnitude 6.7), and shaking intensity ranging up to MMI VII to MMI IX. Chung[41] reported that for first time in LA history electrical power was out in the entire city. It was restored to 90% of LA Dept of Water and Power customers within one day of earthquake.

No type of building came through unscathed. At least 200 three-story wood-framed and stucco-clad apartment buildings collapsed, and a further 650 suffered serious damage. A number of multi-story car parks collapsed due to column failure. Many reinforced concrete office building older than 20 years performed badly due to insufficient reinforcing. Many moment-resisting steel framed building experienced welding failures. Six freeway bridges collapsed.

There are a number of reports and articles written about the fire ignitions associated with this earthquake, and there are some conflicting statements regarding the numbers of events that occurred. In general, these discrepancies are probably due to the many different sources of information that have been used to amass this data. In the following paragraphs a variety of information will be presented without an attempt to compare the validity of the data. There will be a discussion at the end of the section.

Scawthorn, Cowell, and Borden[42] estimate in the period of 4:31 a.m. (time of main shock) to midnight, there were approximately 110 earthquake-related fires. They emphasized the collection, documentation, and preservation of data, with some limited analysis. Fire incident data are compiled in a database termed FFNRE (available on the Internet: www.eqe.com) and details are given for fire departments at 5 selected fire incidents. Limited analysis led to the following most important conclusions:

1. More than 70% (66) of the earthquake-related fires occurred in single-or multiple-family residences.

2. The major cause of ignition was electric arcing as a result of a short circuit, although gas flame from an appliance was also a recurring source of ignition.

3. Escaping natural gas, presumably from a broken gas line, was the single most common ignition material

4. Ignition rates are comparable with prior US earthquakes, and when compared with the San Fernando and Kobe earthquakes, all three events share winter early morning occurrence times.

Scawthorn, et al.[43] also included a discussion on damage to fire stations, water systems and gas systems. They estimated that about 151,000 gas customer outages had occurred, (81% customer initiated) and three months after the earthquake, repairs had been made to about 800 gas systems at separate locations. Of the 8,000 seismic gas shut-off valves in the region, about 10% (841) had tripped off and among those 19% (162) had leaks. One can summarize some of their conclusions as follows:

1. While there were a significant number of fires, they were all brought under control within hours of the earthquake.

2. The LA resources were sufficient to deal with all fire ignitions

3. Water supply failed in heavily affected areas, and firefighters resorted to alternative sources, which, however, would likely not have sufficed had conflagrations developed.

4. Arson fires were not a significant factor

One can infer a list of "*Lessons learned*" within the report of Scawthorn, et al[44]:

1. Alternatives to water need to be developed and water systems need to seismically upgraded

2. Gas and electric seismic shut-off devices offer a potential for mitigation.

3. Multiple fires can be expected as a result of earthquakes in urban areas. The experiences of the Northridge earthquake show that in a larger earthquake more ignitions might result, which may overwhelm the resources of the emergency responders.

4. The weather was not a major factor in the Northridge earthquake, but in future earthquakes it may make the deciding difference. Coupled with inadequacies in the water supply, this may lead to large conflagrations that could rival the 1906 San Francisco earthquake.

Finally, Scawthorn, et al[45] show three photographs of the collapse of the Northridge Meadows apartment at 9565 Reseda Blvd. where 16 persons were killed and "hundreds rescued". One can well imagine how the ratio of "killed-to-rescued" would have been changed had there been a fire in the debris like they report at 11611 Blucher Ave, Granada Hills[46]. The latter structure contained 2-story condominiums that did not trap as many people as the Meadows apartment building.

Todd, Carino, and Chung[47] listed the natural gas leaks as the principal cause of fires with other causes such as hazardous chemical interactions causing a small number of fires. Todd also reported that some fires occurred in the days following the earthquake that were attributable to the restoration of electricity and gas service.

Strand[48] reports that there were 14,062 natural-gas leaks on consumers' lines and cites an unpublished Southern California Gas Company (SoCalGas) report. More significantly, Strand personally performed a survey of the performance of 424 seismic gas shutoff valves and concluded that most of them within a 29 km radius of the epicenter tripped. The closest one that did not trip was 14 km away. Strand also quoted the number 841 tripped seismic gas shutoff valve referenced by Scawthorn, et al[49], but Strand attributes that number to the unpublished SoCalGas report mentioned above[50].

Strand further states that in Los Angeles, leaking gas caused fires in at least 24 single-family dwellings, 5 apartment buildings, 3 businesses, and 6 mobile home parks with a loss of 144 trailers. Causes include broken gas lines to 21 water heaters, 5 trailers, 2 floor heaters, and 2 dryers; leaks in an attic, in a kitchen, at 2 meters, and between a meter and a building. Two more fires occurred due to damaged gas mains, one where a block-wall fell, and another where a large gas main under Balboa Boulevard in Granada Hills ruptured resulting in the loss of 5 homes. Strand also notes that local fire departments and SoCalGas recorded about 60 gas-related structure fires, not including the mobile home fires. One hundred and seventy-six mobile homes were reported to have burned.

The US-Japan Workshop[51] notes that the major ignition sources were electric arcing as the result of a short circuit, and gas flames from an appliance. Southern Cal Gas reported about 2,500 damaged water heaters. Approximately 20 fires were due to inadequately secured water heaters tipping over.

According to Chung[52], the water heater was the most vulnerable appliance. He quoted that approximately 2,500 water heaters were damaged during this earthquake, and approximately 20 fires were due to inadequately secured water heaters tipping over. After the earthquake, Chung noted that the technical feasibility of seismically operated shut-offs and control mechanisms should be assessed along with a cost/benefit analysis for the use of these systems. Guidelines for the installation and use of these devices should be developed. He also suggested that earthquake-activated electric shutoff switches should be assessed. He noted that these should have some value for the following two scenarios:

1. When damage to electric service has occurred, particularly in buildings sustaining serious structural damage. This may include faults to ground and short circuits that could act as potential ignition sources.
2. When electric service is restored, before the removal of combustibles that have toppled over and fallen on electrical appliances.

The Hyogo-ken Nanbu (Kobe), Japan, Earthquake of 1995

The Hyogo-ken Nanbu earthquake occurred at 5:46 am on 17 January 1995 with a with a moment magnitude of 6.9 (Richter magnitude 7.2), resulting in shaking intensity exceeding MMI VIII. Nearly 6,000 people were killed, and over 33,000 injured. Many were trapped alive in collapsed buildings and killed by the firestorms that followed. Over 500 deaths were caused by fire.

According to Sekizawa[53], for cities other than Kobe, about 73% of fires that started by 6:00 am on the day of earthquake were single fires confined to structure of origin. About 3% of these fires spread to be large fires having burned an area greater than 1,000m^2. This indicates that the fire brigades functioned fairly well in regions other than Kobe.

Sekizawa[54] discusses the causes of fire ignition and noted that when one excludes unknown fire causes, most fires were derived from "gas leakage or gas apparatuses" and "other fire apparatuses or chemicals" rather than "electrical causes" for fires occurring by 6:00 a.m., i.e. shortly after the main shock. With the elapse of time, the proportion of these fires decreased and the proportion of electrical causes increased and became the main source of ignition after 7:00 a.m., when the electrical service was being restored.

Chung[55] reports the following combinations of fuels and ignition sources that most likely caused the fires: broken natural gas pipes that were evident at many of the fire sites of homes and factories; kerosene heaters that were present in the ruins of many of the buildings; power lines knocked down by the earthquake or torn from collapsed buildings; activities associated with the recovery activities such as use of candles and fires for warming displaced survivors getting out of control; and arson. Chung also partially supports the theory that when electric power was restored, damaged appliances, wiring, and light fixtures ignited combustibles.

According to NZNSEE[56], there does not appear to have been a close liaison with gas and electricity suppliers before power was restored. The rapid reinstatement of power was a significant cause of fire ignitions.

Inventory of Post-Earthquake Fire Scenarios

The fire aspects of eleven different damaging twentieth century earthquakes have been presented in this section. They started with the 1906 San Francisco event and ended with the 1995 Kobe event. The eleven events were chosen to illustrate the range of fire scenarios that can follow an earthquake. The eleven events appear to follow Sekizawa's observation[57] that "the incidence of fires following an earthquake is in proportion to the ratio of damaged-to-undamaged structures". Structural damage relates directly to disruption of gas pipes and gas appliances and the damage of electrical wires or electric appliances, a fraction of which in turn lead to fire ignitions fed by gas leakage or electric arcing.

IGNITION SCENARIOS

An analysis of the eleven large twentieth century earthquake occurrences yields a list of ignition scenarios in which the gas and/or electric service played a role in the ignition of the first fuel in the fire:

1. A gas pipe in a building is broken, **and** an electric arc from damaged electrical wiring is present near the released gas to ignite it promptly.
2. Bottles and/or open cans of flammable liquids are thrown to the floor by the earthquake, **and** an open gas flame or an electric arc is present to ignite the vapors from the spilled liquid.
3. A hot water heater is overturned by the earthquake motions resulting in a rupture of the gas supply piping, **and** the released gas is ignited by the pilot light of the heater.
4. A gas pipe in a building is broken because the structure deformed so much that pipe could not remain undamaged **and** the delayed ignition of the released gas occurs when an ignitable mixture of gas and air has been created. This scenario can lead to an explosion[&]. The ignition can vary for this scenario. Certainly, rescue efforts can potentially be a significant source of ignition.
5. Cooking oils and other kitchen fuels are spilled during the earthquake, **and** either electrical- or gas-based cooking equipment ignites these fuels
6. While the electrical service to a structure is interrupted by the initial earthquake event, an electric-powered device is displaced and/or damaged by the earthquake motions and put into contact with a quantity of fuel. Then when the electric power is restored to the building, this displaced device causes the ignition of the exposed fuel. An example of such a scenario might be a high intensity light falling onto a polyurethane mattress or couch.
7. A person ignites a fire by such means as arson or turning on light switches with natural gas present.

[&] The term "explosion" can be used to describe a range of phenomena. If the gas and air are well mixed the ignition of the pre-mixed gas cloud can result in a "detonation" with the release of a great deal of energy and supersonic shock waves. If the gas cloud has not mixed with air to a large extent, and if the ignition occurs at a boundary of the gas cloud where air is present, the burning of the gas can cause local turbulence which in turn causes more air to mix with the gas cloud that accelerates the burning. This accelerated burning leads to a "deflagration" which sounds like and looks like an explosion, but it lacks the energy release and the destructive power of a detonation.

Our analyses do not focus equally on all of the above scenarios for the following reasons. These scenarios are for ignition of the first fuel, but the life-safety and property-damage impact of various post-earthquake fire scenarios depends much more on other factors than the initial first fuel ignition. The time of day, which affects the various activities of people, can have a large impact on the consequences of post-earthquake fires. In the same fashion, the type of occupancy of a building can change the life-safety impact more than any other feature of the structure. We are focusing on residential occupancies in this report, because the potential life- safety implications are much greater in this sector. Other occupancies such as elementary schools and hospitals, have received special treatment in the building codes for seismic safety resulting in less potential for harm in those structures than in residential structures.

Post-Ignition Residential Fire Scenarios

Residential occupancies differ according to the number of residential units that are located within a building. The number of units within a building is important to fire safety for many reasons. For example, building layouts differ as to whether occupants must use shared paths of emergency egress or they can leave the building by a direct unshared route. In multiunit occupancies (R-1 occupancies**), common paths of egress and limited means of escape make it more likely that persons can become trapped after an earthquake. The greater the number of occupants in a building, the greater is the likelihood of their being trapped. The possibility of structural damage that prevents the operation of doors leading out of apartment and condominium units often cause this inability to exit safely. In buildings of more than two or three stories, the escape paths usually include enclosed stairways whose doors can be jammed by the racking deflections of the doorframes caused by the earthquake. Frequently, the elevators in these buildings are also unusable. Some older buildings may have exterior fire escapes, but they may not be well attached after the earthquake. Single-family residential units (R-3 occupancies), on the other hand, cannot, by code, be more than 3 stories in height, and their windows are usually constructed in such a way that they can serve as secondary exits[58]. Thus there are more and easier pathways for escape in R-3 occupancies than is generally true in R-1 occupancies. In addition, if the R-3 structure is properly tied to its foundation, such a building is less likely to lose its means of escape than the larger and more complex R-1 structures.

Mallick and Saud[59] wrote about post-earthquake scenarios in the context of a "developing country like India" in which the "earthquake aftermath presents a scenario of collapsed and damaged buildings and bridges, fires raging out of control, people trapped inside the burning houses and/or under the debris of collapsed buildings". In many ways, their scenarios could also be appropriate for the more developed countries under conditions of damaged R-1 structures in dense urban areas.

A great deal of the attention in the US has been on conflagrations following earthquakes as being the most damaging fire impact of earthquakes. This scenario has been well developed by Scawthorn[60] who notes that fires following earthquakes have caused the largest single losses due to earthquakes in the United States and Japan. He

** Occupancies are defined in the model building codes; R-1 and R-3 are the designations for residential occupancies, see Table 1.

considers the following factors in scenarios for post-earthquake fires: structural and non-structural damage, initial and spreading fires, wind, building density, water supply functionality and emergency response. He has written an analytical model that has been the basis of several computer models that have been applied to predict the conflagration potential of various possible earthquakes

SYSTEMS APPROACH TO POST-EARTHQUAKE FIRE SAFETY

A fire must go through many stages before it becomes a conflagration. Once an ignition occurs within a space in a building, the fire will have to grow in size that is a process that can be described by an "Event Tree". In most interior spaces, fire spread will not occur unless there is "flashover" in the room-of-origin, which depends on many factors including other sources of fuel, damage to surrounding structural elements, and housekeeping. Many different fire scenarios may occur, and small changes in the conditions can make a large difference in the outcome of the fire ignition. For instance, whether a door is open or closed can make a very significant difference. If the occupants can escape from a building, the principle impact of the fire is one of property damage rather than of life-safety if the people cannot escape. One of the best ways to describe these differences is through the use of the "Systems Approach" for fire safety.

A good starting point for analyzing the fire safety associated with a given operation or structure is the "Fire Safety Concepts Tree [61] or "Decision Tree" as developed by the National Fire Protection Association (NFPA) on Systems Concepts for Fire Protection in Structures. It can be used as a checklist for the analysis. The Fire Safety Concepts Tree is essentially a generalized goal decomposition intended to be applicable to any structural fire safety problem. Like the focused goal decomposition presented later in this report, it uses an ends-means logic to associate more abstract goals to more specific strategies for achieving those goals. Thus, it provides a good introduction to the special problems associated with fire safety during earthquakes.

Starting at the top with the **Fire Safety Objective(s)**, the tree proposes alternative ways, not necessarily mutually exclusive, of meeting those objectives. The first choice in the tree is to **Prevent Fire Ignition** or **Manage the Fire Impact**, as shown in Figure 1. The objectives can be listed as

(1) Prevention of loss of life or personal injury,

(2) Prevention of the loss of property,

(3) Prevention of the interruption of business,

(4) Prevention of environmental damage,

(5) Prevention of loss of historical artifacts and buildings, and

(6) Preservation of emergency response, hospitals, water response, etc., in the post-earthquake environment.

The small box with the "+" is an "or gate" which signifies that the objectives can be achieved by either of the two choices. In practice, it is usually not possible to just follow one approach, but the "or gate" represents the logical relationship between the two sides of the tree. Thus in principle, if you prevent the ignition, you will reach the objectives.

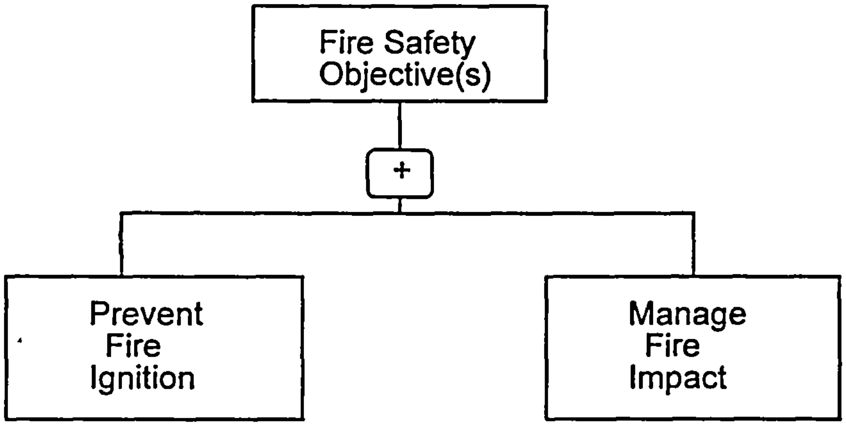

Figure 1. The principal branches of the "Fire Safety Concepts Tree" or "Decision Tree," as developed by the NFPA on Systems Concepts for Fire Protection in Structures.

The branch of the Decision Tree headed by **Prevent Fire Ignition** is followed by an "or gate" and three choices that are relatively independent of each other. This branch is shown in Figure 2. The prevention of ignition is divided into **Control of Heat-Energy Source(s), Control of Source-Fuel Interaction,** and **Control of Fuel,** and the goal of preventing the ignition can be achieved, in principle, by controlling any one of those entries in the tree. In the post-earthquake scenarios, if there is a gas leak then the control of the fuel has been lost and thus the ignition event can only be prevented if the potential ignition sources and their interaction with the gas leak are controlled.

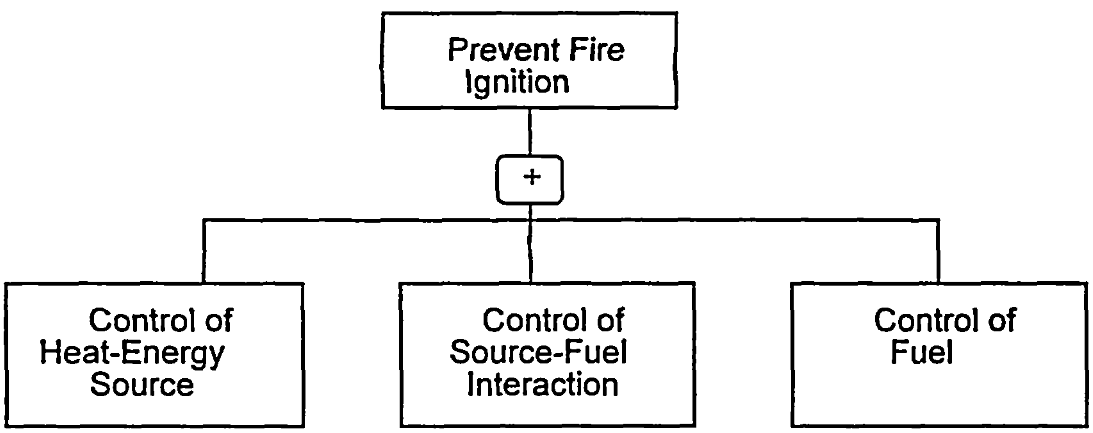

Figure 2. The branch of the Decision Tree headed by **Prevent Fire Ignition** has three choices that are relatively independent of each other.

If one is not successful in preventing the fire ignition, then the decision tree gives an alternate solution that is given on the right-hand side of the tree, under **Manage (the) Fire Impact.** There the choices are either to **Manage the Fire** or **Manage the Exposed,** as shown in Figure 3.

Thus if one option does not prevent the ignition, the tree indicates that one has the alternate option of managing the impact of the fire by either managing the fire itself or managing the exposed people, property or operations to prevent the loss.

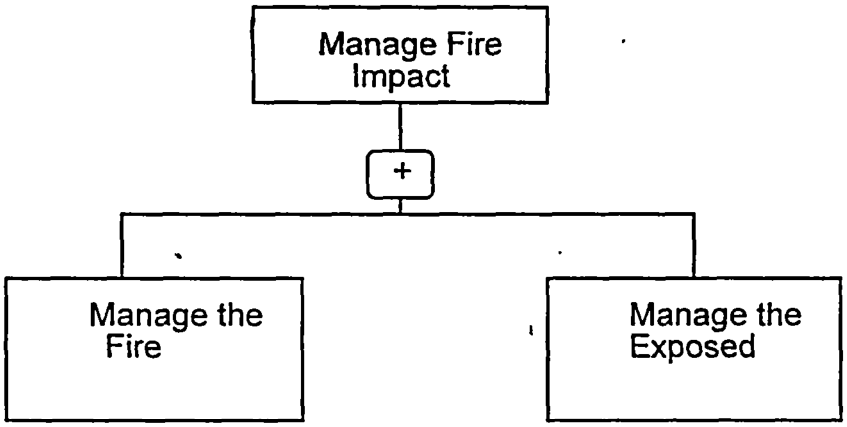

Figure 3. The choice of reducing fire impacts is divided into Managing the Fire or Managing the Exposed people, property or operations.

The top three levels of the NFPA Decision tree are shown in Figs. 1, 2, and 3. For the post-earthquake environment it is important to point out that this Fire Safety Concepts Tree or Decision Tree is a "success tree" because the top items represent a successful application of fire safety logic. This tree can be converted to a "fault tree" by changing all the "and gates" to "or gates" and all the "or gates" to "and gates"[@]. Thus one can have a large loss of life in a fire in which the ignition had occurred and the fire impact was not controlled. The Fire Safety Concepts Tree has three or four additional levels of detail below those shown in Figs. 1, 2, and 3, but for our purposes the levels shown here are sufficient.

In the post-earthquake environment, the probability of managing the fire impact is reduced. To Manage the Fire Impact, one either has to manage the fire by applying fire suppression or containing it in compartments bounded by fire-resistant construction, for example, or one has to Manage the Exposed people, property or operations. If we consider life safety, there are two ways to Manage the Exposed people: (1) cause them to move to safety, or (2) defend them in place. Both these approaches are inconsistent with damaged or partially collapsed buildings where people are trapped inside, which is one of the most life-threatening fire scenarios.

[@] This is true with regards to the fire safety concepts tree, and in general, it is accurate to say that a success tree can be changed to a failure tree by reversing the gates. However, fault trees use a causal logic to link event nodes, while a success or goal tree uses ends-means logic to link nodes that vary in their level of abstraction.

GOAL DECOMPOSITIONS

Goal decompositions have the advantage of solving problems by breaking down general desirable systems states into continually more specific and measurable goals. Eventually, goals can be decomposed into all the specific actions that various parties should consider in their effort to realize general goals such as preventing casualties and property damage and minimizing expenses. The word "scenario-based" has been added to goal decompositions to distinguish the context in which it will be applied. Thus it will be called "scenario-based goal decomposition" (SGD). Groner and Williamson [62] describe this approach as an "intentional systems" model to design and evaluate fire safety systems. Scenario-based goal decomposition differs from traditional engineering methodologies that rely on physical (causal) models where events are driven by laws of causation. Instead, SGD represents fire scenarios as a series of desirable system states that are driven by goals. These goals originate with the people who design for a fire emergency (e.g., fire protection engineers and emergency planners) as well as those who participate during an emergency (e.g., building occupants, utility staff, fire fighters, and others). The SGD approach defines fire safety goals as desirable states for a "fire safety system." A fire safety system is viewed as being comprised of all relevant components, including people, which play significant roles in the defense against a fire threat. In a goal decomposition analysis, desirable system states are "decomposed" to increasingly specific and measurable levels. Various fire scenarios often present many different elements where trade-offs can substitute hardware for action or visa-versa. If we paraphrase Groner[63]: "When evaluating and designing fire safety plans, it is important to understand that weakness in the system can be offset by improving capabilities in another part of the system. Hardware is used to compensate for limitations in procedures, and procedures are used to compensate for limitations of hardware." This principle cuts across types and categories of components.

A schematic goal decomposition model for utility-related earthquake fires is shown in Figure 4. Separate symbols are shown for "Intentional Systems States" and "Lowest Level System States". Figure 4 is divided into four parts that show how the goal decomposition model can detail some of the more specific means for preventing fire ignitions in individual buildings. The reader, however, is cautioned that the means provided are not exhaustive. The model is presented as an example of how a goal decomposition can be used to link high level objectives to the very specific strategies that can be used to accomplish them.

The model can be extended to allow the calculation of probabilities associated with the prevention of ignition in a specific type of building. When the number of such buildings is known for a selected geographical area, the probability of preventing ignitions in that area can be calculated. The probability of preventing an ignition in a particular building can be calculated when the probabilities for the specific low level enabling states is known. Various means for obtaining such probabilities might include historical data and expert judgment.

Scenario-Based Goal Decomposition for Gas-related Fire Ignitions inside Residential Dwelling Units during Earthquakes

Goals are defined as desirable system states. Desirable systems states are "decomposed" into increasingly specific levels of definition. System states are divided into two types. "Scenario" system states are those states which are not under consideration for manipulation (rounded corners). "Intentional" system states are being considered for manipulation (sharp corners).

Logic gates and calculations of probabilities are the same as for event trees (e.g., fault trees). Probabilities are assigned to system states are for a single type of residential dwelling (e.g., detached one- and two- family residences. Regional risk assessment requires the multiplication of the top probability of preventing ignition by the number of dwellings of a specific type.

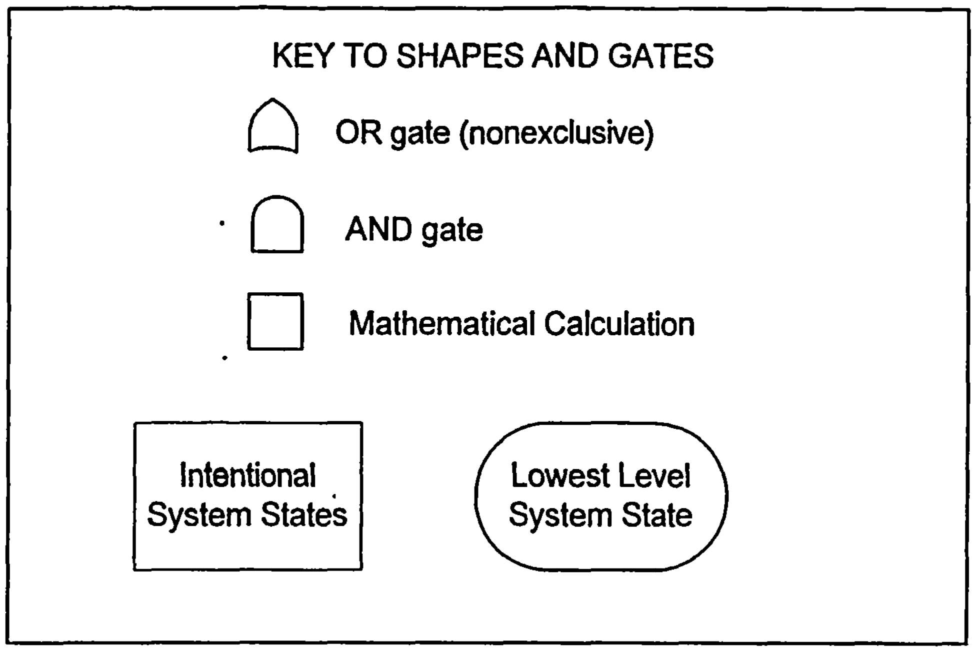

Fig. 4 (a)

SCENARIO: Fire ignitions related to gas line faults inside 1 & 2 Family residential dwelling buildings, (i.e., R-3 Occupancies by '97 UBC). This model calculates the probabilities of desirable system states associated with preventing earthquake related fires where natural gas is the first ignited fuel. It does not include ignitions unrelated to gas as a fuel or associated with the restoration of gas service.

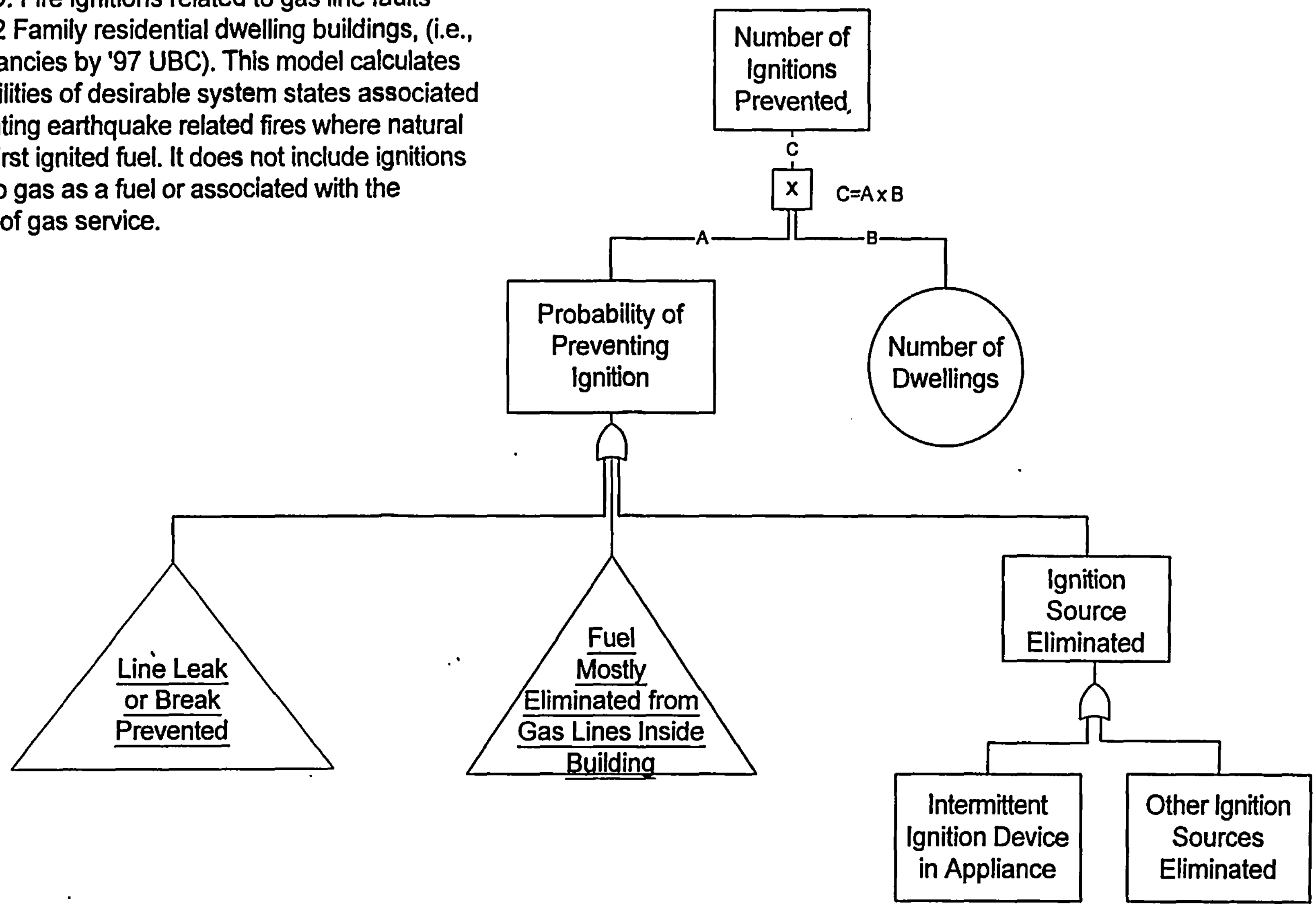

Fig. 4(b)

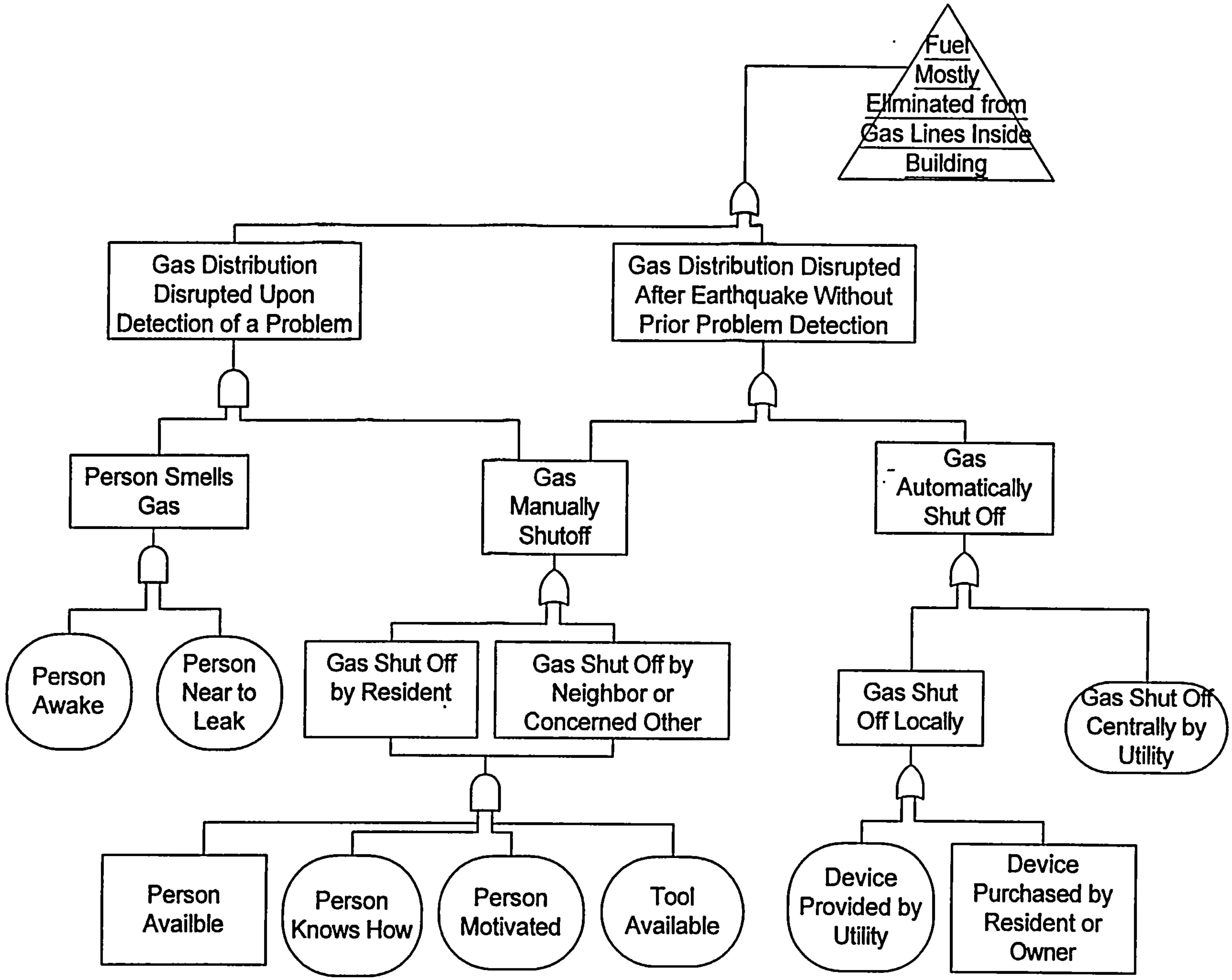
Fuel
Mostly
Eliminated from
Gas Lines Inside
Building
Gas Distribution Disrupted Upon Detection of a Problem
Gas Distribution Disrupted After Earthquake Without Prior Problem Detection
Person Smells Gas
Gas Manually Shutoff
Gas Automatically Shut Off
Person Awake
Person Near to Leak
Gas Shut Off by Resident
Gas Shut Off by Neighbor or Concerned Other
Gas Shut Off Locally
Gas Shut Off Centrally by Utility
Person Availble
Person Knows How
Person Motivated
Tool Available
Device Provided by Utility
Device Purchased by Resident or Owner

Fig. 4(c)

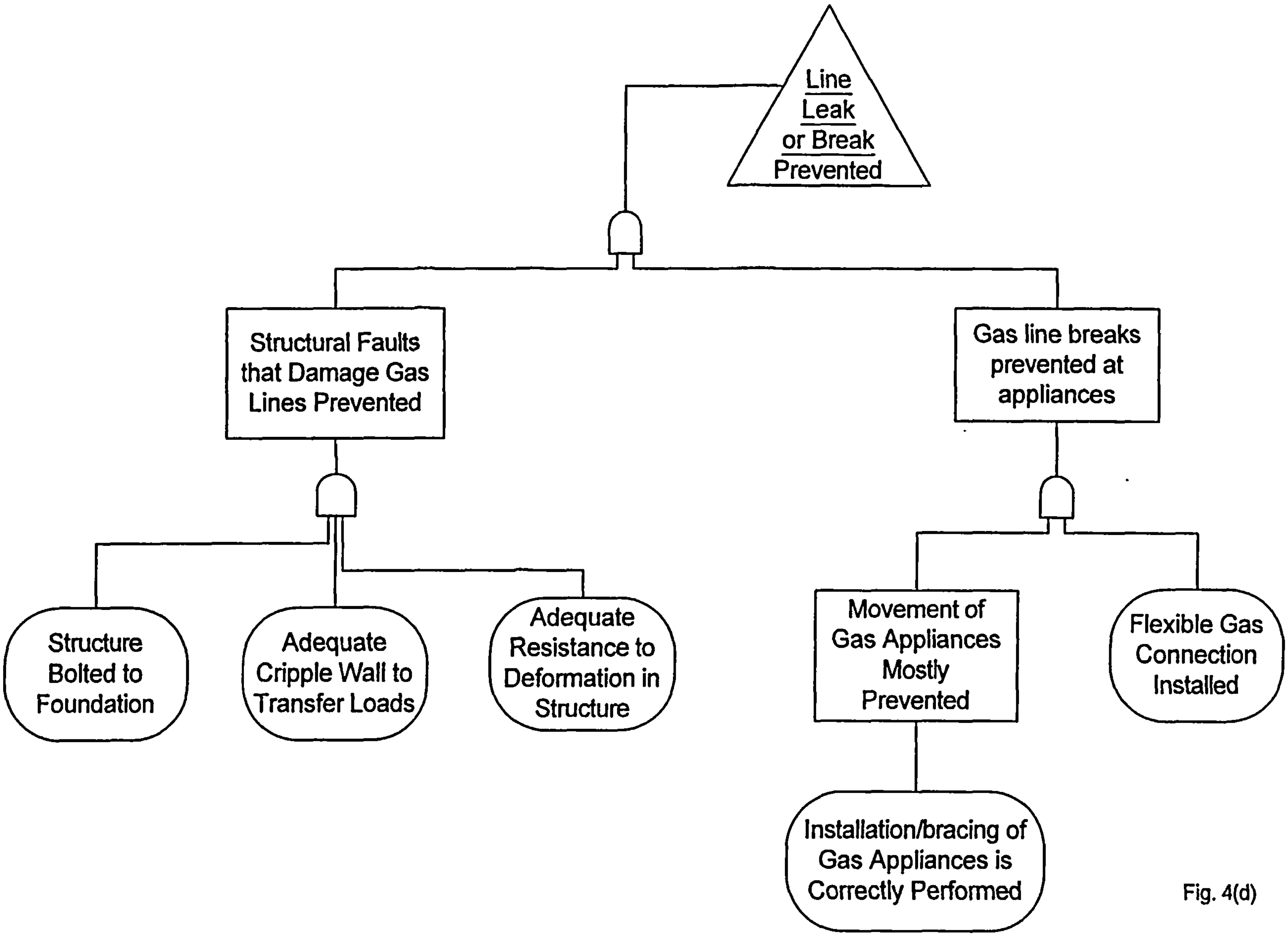
Line Leak or Break Prevented
Structural Faults that Damage Gas Lines Prevented
Gas line breaks prevented at appliances
Structure Bolted to Foundation
Adequate Cripple Wall to Transfer Loads
Adequate Resistance to Deformation in Structure
Movement of Gas Appliances Mostly Prevented
Flexible Gas Connection Installed
Installation/bracing of Gas Appliances is Correctly Performed

Fig. 4(d)

GAS LINE FAULT IGNITION IN ONE AND TWO FAMILY DWELLINGS

Table 1 gives short descriptions of the *"Residential"* Occupancies, as defined by the 1997 Uniform Building Code[64] where one and two family dwellings are defined. Note they are called "Group R-Division 3", (or R-3, for short) occupancies. The "top state" in Figure 4(b) is the "Number of Ignitions Prevented" which is dependent on two elements: (1) the Probability of Preventing Ignition, and (2) the Number of Dwellings. The number of dwellings is given by the scenario and is therefore "intractable[+]", but the Probability of Preventing Ignition can be influenced by three different activities. The first is "Line Leak or Break Prevented" which is the "top state" in the diagram shown on Figure 4(d) where the two principle ways of achieving this goal are connected with an "and" gate since they both must be accomplished to prevent the gas line from breaking.

TABLE I. RESIDENTIAL OCCUPANCIES AS DEFINED BY THE 1997 UNIFORM BUILDING CODE

GROUP R. "Residential" Occupancies are defined in Section 310 of the UBC as follows: **Division 1.** Hotels and apartment houses. Congregate residences (each accommodating more than 10 persons) **Division 2.** Not used. **Division 3.** Dwellings and lodging houses. Congregate residences (each accommodating 10 persons or less)
Definitions as defined in Chapter 2 of *UBC:*
Dwelling Unit *is any building* or portion thereof which contains living facilities, including provisions for sleeping, eating, cooking and sanitation as required by this code, for not more than one family or a congregate residence for 10 or less persons.
Dwelling is any building or portion thereof which contains not more than two dwelling units.
Apartment House is any building or portion thereof which contains three or more dwelling units and, for the purpose of this code, includes residential condominiums.
Congregate Residence is any building or portion thereof which contains facilities for living, sleeping and sanitation, as required by this code, and may include facilities for eating and cooking, for occupancy by other than a family. A congregate residence may be a shelter, convent, monastery, dormitory, and fraternity or sorority house but does not include jails, hospitals, nursing homes, hotels or lodging houses.

The second approach to Preventing Ignition is "Fuel Mostly Eliminated from Distribution" which is the "top state" in the diagram shown in Figure 4(c). Here the two principle ways of achieving this goal are connected with an "or gate," since they are alternative means of achieving the same results. Up to this point we have been applying simple logic and known methods of strengthening buildings for earthquake damage, but in Figure 4(c) the underlying assumption is based on fire science. The element of fire science is that it requires more than 30 seconds of continuous gas flame impingement to ignite most wooden building components. The ignition times for two exposures are shown below in Table 2.

[+] The number of dwellings subjected to a given level of earthquake exposure depends on the details of the earthquake source, the soil/rock conditions at each building, and the distribution of the buildings around the earthquake source.

TABLE 2. IGNITION TIMES FOR WOODEN BUILDING MATERIALS*

MATERIAL	IGNITION TIME, T_I, SEC	
	25 FT. TUNNEL	20 LB CRIB/CORNER
Untreated♦ Wood Fiberboard, ½ in. (12.7mm)	32	25
Untreated♦ Plywood, ¼ in. (6.35)	32	50
Untreated♦ Wood Particle Board, ½ in. (12.7mm)	60	90
Untreated♦ Plywood, 11/64 in. (4.4 mm)	60	93
Treated♣ Plywood, ½ in. (12.7mm)	90	80
Treated♣ Wood Particle Board, ½ in. (12.7mm)	100	265

♦"Untreated" means it is not "fire-retarded", and ♣ "Treated" means it is "fire-retarded"

The "25-ft. tunnel" data were obtained in the *ASTM E-84 Standard Test Method for Surface Burning Characteristics of Building Materials*[65] in which the sample is exposed to an 88 kW natural gas diffusion flame that impinges on an area approximately 1.5 ft (0.46 m) wide by approximately 4.5 ft (1.37 m) long. The "20 lb (9.07 kg) wood crib" exposure is a burning stack of small sticks with a heat release rate of approximately 120 to 180 kW. Both ignition sources give approximately the same ignition times. It is assumed that in the post-earthquake environment of an ignited gas source, it would require more than a minute of continuous flaming to ignite materials around the diffusion flame. The diagram on Fig. 4 (c) shows either a manual or an automatic shutoff of the gas supply to the dwelling. Another illustrated approach is to eliminate the ignition source and thereby preventing ignition of the leaking gas[#,&] The overall assumption in this approach is that the gas supply to the dwelling is not interrupted, thus allowing natural gas to continue to leak into the building with the potential of a fire or explosion if an ignition is exposed to the gas/air mixture.

INFLUENCE DIAGRAMS

Influence diagrams have the advantage of showing the dynamic relationships between events and/or systems states over time. A general model of fire ignition related to gas and electrical service during earthquakes is shown in Figure 5(a). As more details are added, the model can be modified and changed in many different ways.

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[*] Excerpt from Flammability Studies of Cellular Plastics and Other Building Material Used for Interior Finishes, Underwriters Laboratories, Inc., Northbrook, IL, 1975

[#] Fire Protection Engineers do not rely solely on the prevention of ignition as a reliable fire safety measure. Note discussion for Fig. 2.

[&] The notes shown in Fig. 5 are not necessarily complete. For instance, an additional system state during disruption and restoration that is missing is the utility's ability to shut off the sections of the gas distribution system to isolate an area that is damaged. This can be done in several ways including zone valves, squeezing the main if a valve is not available, and in a catastrophic situation shutting off the supply of gas from its supply source, typically pressure regulating stations off the transmission line.

GENERAL MODEL OF FIRE IGNITION

RELATED TO GAS AND ELECTRICAL SERVICE

DURING EARTHQUAKES

Influence Diagrams 5a – 5d

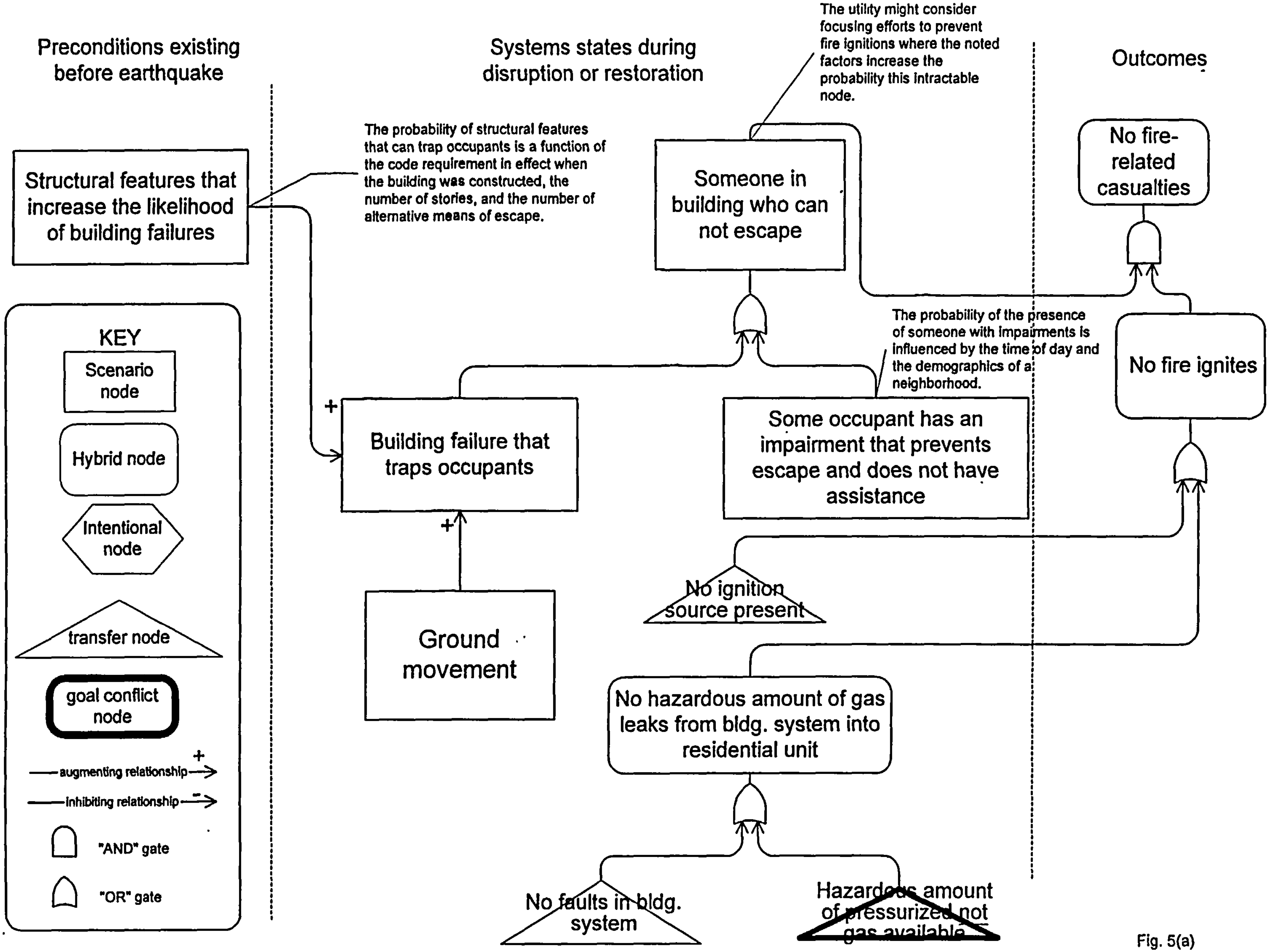
Preconditions existing before earthquake
Systems states during disruption or restoration
Outcomes
Structural features that increase the likelihood of building failures
The probability of structural features that can trap occupants is a function of the code requirement in effect when the building was constructed, the number of stories, and the number of alternative means of escape.
Building failure that traps occupants
Ground movement
Someone in building who can not escape
The utility might consider focusing efforts to prevent fire ignitions where the noted factors increase the probability this intractable node.
Some occupant has an impairment that prevents escape and does not have assistance
The probability of the presence of someone with impairments is influenced by the time of day and the demographics of a neighborhood.
No ignition source present
No hazardous amount of gas leaks from bldg. system into residential unit
No faults in bldg. system
Hazardous amount of pressurized not gas available
No fire-related casualties
No fire ignites
+
+
KEY
Scenario node
Hybrid node
Intentional node
transfer node
goal conflict node
augmenting relationship +
inhibiting relationship -
"AND" gate
"OR" gate

Fig. 5(a)

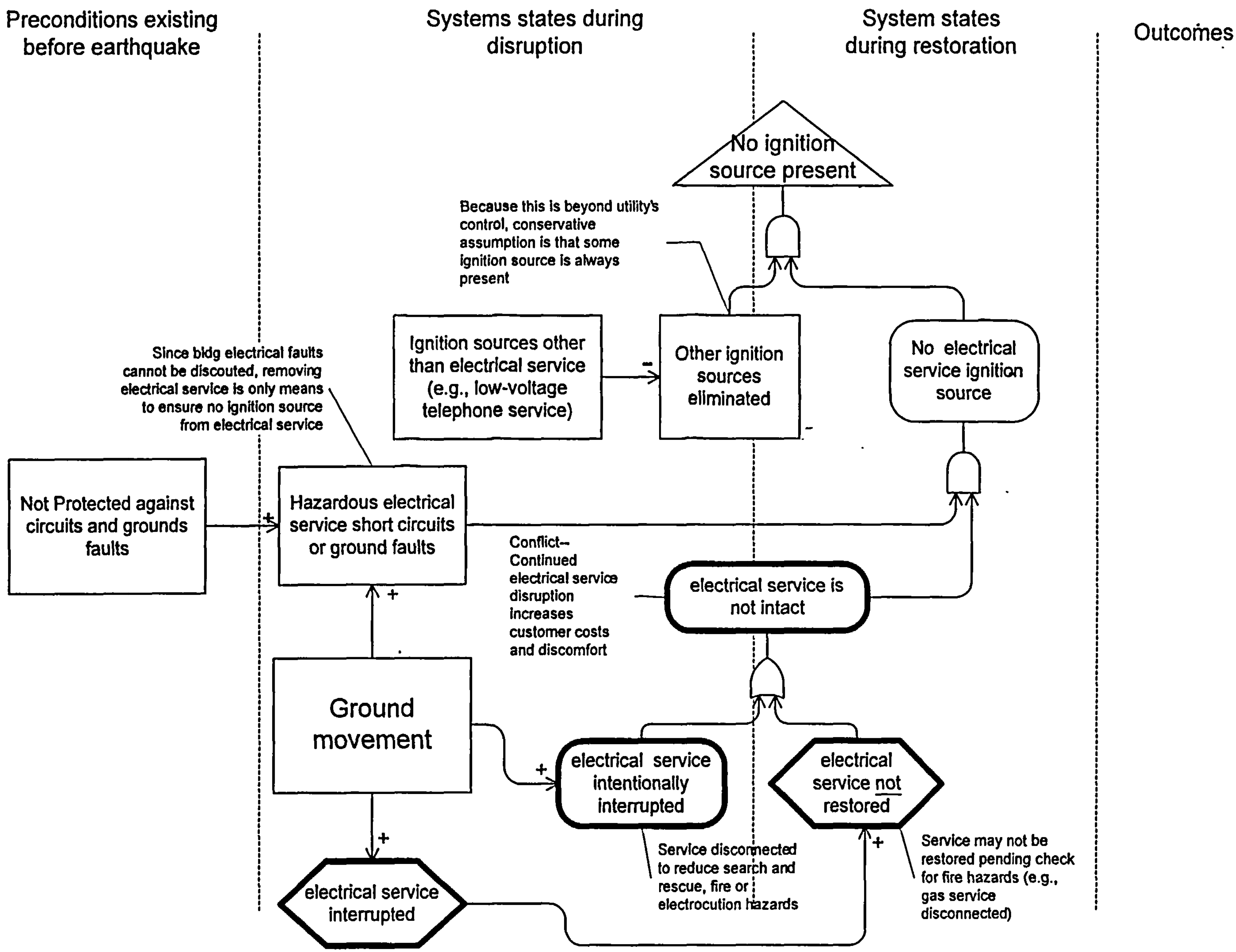
Preconditions existing before earthquake
Systems states during disruption
System states during restoration
Outcomes
No ignition source present
Because this is beyond utility's control, conservative assumption is that some ignition source is always present
Ignition sources other than electrical service (e.g., low-voltage telephone service)
Other ignition sources eliminated
No electrical service ignition source
Since bldg electrical faults cannot be discouted, removing electrical service is only means to ensure no ignition source from electrical service
Not Protected against circuits and grounds faults
Hazardous electrical service short circuits or ground faults
Conflict-- Continued electrical service disruption increases customer costs and discomfort
electrical service is not intact
Ground movement
electrical service intentionally interrupted
electrical service not restored
Service disconnected to reduce search and rescue, fire or electrocution hazards
Service may not be restored pending check for fire hazards (e.g., gas service disconnected)
electrical service interrupted

Fig. 5(b)

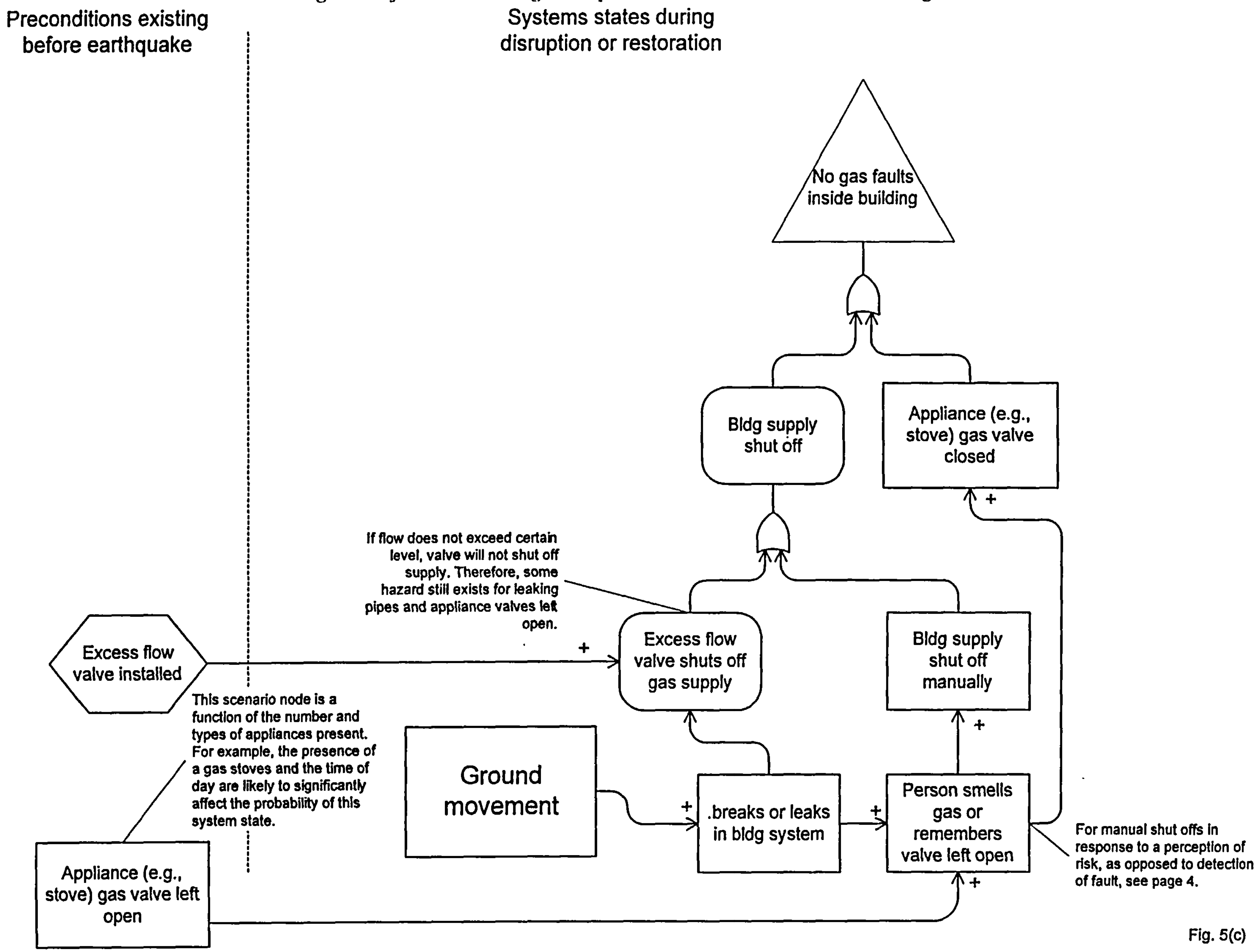
Preconditions existing before earthquake
Systems states during disruption or restoration
No gas faults inside building
Bldg supply shut off
Appliance (e.g., stove) gas valve closed
If flow does not exceed certain level, valve will not shut off supply. Therefore, some hazard still exists for leaking pipes and appliance valves left open.
Excess flow valve installed
Excess flow valve shuts off gas supply
Bldg supply shut off manually
This scenario node is a function of the number and types of appliances present. For example, the presence of a gas stoves and the time of day are likely to significantly affect the probability of this system state.
Ground movement
.breaks or leaks in bldg system
Person smells gas or remembers valve left open
For manual shut offs in response to a perception of risk, as opposed to detection of fault, see page 4.
Appliance (e.g., stove) gas valve left open
+

Fig. 5(c)

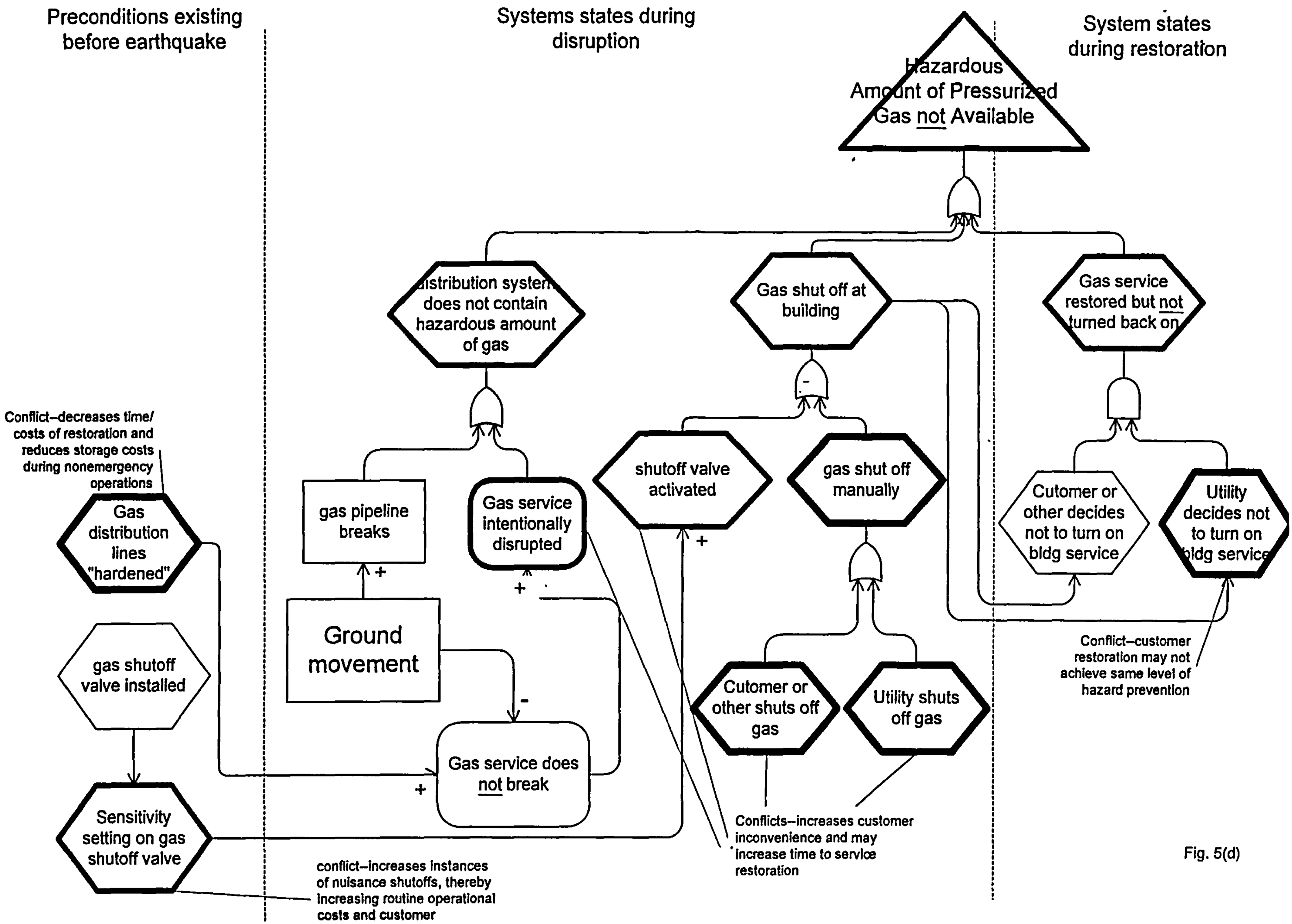
Preconditions existing before earthquake
Systems states during disruption
System states during restoration
Hazardous Amount of Pressurized Gas not Available
distribution system does not contain hazardous amount of gas
Gas shut off at building
Gas service restored but not turned back on
Conflict--decreases time/ costs of restoration and reduces storage costs during nonemergency operations
Gas distribution lines "hardened"
gas shutoff valve installed
Sensitivity setting on gas shutoff valve
gas pipeline breaks
Ground movement
Gas service intentionally disrupted
Gas service does not break
shutoff valve activated
gas shut off manually
Cutomer or other shuts off gas
Utility shuts off gas
Cutomer or other decides not to turn on bldg service
Utility decides not to turn on bldg service
Conflict--customer restoration may not achieve same level of hazard prevention
Conflicts--increases customer inconvenience and may increase time to service restoration
conflict--increases instances of nuisance shutoffs, thereby increasing routine operational costs and customer
+
-

Fig. 5(d)

In Figure 5, nodes (events or system states) are related to time by assigning them to four groups: 1. Preconditions that exist before the earthquake; 2. States that occur during system disruption; 3. System states that occur during restoration efforts; and 4. Outcomes (i.e., criteria for measuring the success of systems behavior). Nodes are of three types: 1.Scenario (uncontrolled events or systems states); 2. Intentional (events or system states that the gas and electricity provider(s) can directly affect); and 3. Process/outcome (events or states that the gas and electricity provider(s) can indirectly affect via one or more intentional nodes). These diagrams will be further discussed later in this report. They are shown here to introduce some of the important ideas and to illustrate a way to depict them for subsequent analysis. Further systems states that involve goal conflicts are identical. Certain system states are desirable from a fire safety standpoint, but are undesirable from the standpoint of delays in service restoration causing customer inconvenience, unsafe service restoration performed by inadequately trained personnel, financial costs to customers and utilities, etc.

Alternate Means to Reduce Fire Risks Following Earthquakes

Relationship between Earthquake Shaking Intensity and Fire Occurrence

The likelihood of the occurrence of a fire scenario is dependent on the damage caused by the earthquake. If the intensity of shaking is moderate, certain situations make it more likely for fire ignitions to occur. For instance, if hot water heaters are not equipped with flexible gas supply lines and are not reinforced to prevent rocking or overturning, they may topple and lead to a number of ignitions that could occur even with a moderate earthquake intensity. On the other hand, for properly anchored water heater with a flexible connection, even very severe shaking intensity levels will likely cause only isolated water heater failures, and only a fraction of those will result in ignition. A correlation between ground movement and damage is usually expected, as indicated in the review of past earthquakes and revealed in the abridged table of "observed effects" for various MMI values (Table 3).

Our analyses of scenarios reveal the possibility of a paradoxical and unintuitive nonlinear relationship between the intensity of ground movement and the likelihood of gas-fueled fires. For example, at a lower earthquake intensity of an MMI of VI or VII, a hot water heater that is not equipped with a flexible gas supply line and is not reinforced to prevent rocking or overturning will probably fail, releasing gas. Yet, the distribution system will probably remain intact, ensuring a large supply of escaping gas. At a higher MMI of perhaps XI, the water heater will more likely fail. However, the gas distribution could also fail particularly older more fragile distribution systems constructed of brittle pipe and with poor support conditions, preventing the release of large amounts of gas inside the building, thereby reducing the probability of gas-fueled ignitions. In this case, the relationship between earthquake intensity and gas-fueled fires is apt to be nonlinear.

In unusual land conditions in California, there is the potential for a non-linear relationship between the intensity of ground shaking and the likelihood of gas-fueled fires. In these situations, buildings are constructed on soil conditions that are vulnerable to large ground failures and significant displacements due to landslides or liquefaction and lateral spreading. As a consequence, gas distribution mains or service connections can be severed, quickly stopping the supply of gas to connected buildings. Damage in these buildings would not lead to fire because of the lack of available gas leaking into the structures. In limited areas in Northern California, high levels of earthquake-caused damage to cast iron gas distribution pipe could also interrupt the supply of gas. This type of pipe is being replaced by modern ductile pipe, which is highly resistant to earthquake effects. Aside from these special situations, greater shaking severity will generally lead to higher levels of building damage in seismically vulnerable structures, and to more fire ignitions. This is particularly true where the gas distribution system has been upgraded to give better seismic performance.

TABLE 3 MODIFIED MERCALLI INTENSITY SCALE (ABRIDGED)[66] This table contains changes which have been introduced by the authors of this report that are written in *italics (with underlining).* Some other entries from the reference are highlighted with **bold type** because they are significant for the subject of this report.

EARTHQUAKE INTENSITY (MMI)	OBSERVED EFFECTS
VI	Felt by all; many frightened and run outdoors. ***Some heavy furniture moved***; a few instances of fallen plaster or damaged chimneys. Damage slight.
VII	Everyone runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly or badly designed structures; some chimneys broken. Noticed by persons driving motor vehicles. *Most hot water heaters that are not tied down will probably fall over and potentially start fires.*
VIII	Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. *Modern 1 and 2 family structures (R-3 occupancies) are generally not damaged.* Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Disturbs persons driving motor vehicles.
IX	Damage considerable even in specially designed structures; well designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. *Underground pipes broken that have not been designed to take this level of seismic shaking.*
X	Some well-built bridges **and wooden structures seriously damaged**; most masonry and frame structures with foundations **destroyed**; **ground** badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks.
XI	Few (if any) masonry structures remain standing. Bridges destroyed. Broad fissures in ground. *Brittle, and non-seismically designed* underground pipe lines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.
XII	Damage total to non-seismically designed structures. Waves seen on ground surfaces. Line of sight and level distorted. Objects thrown upwards into the air.

Reducing Gas Faults Inside Buildings

The portion of the general influence diagram model shown in Figure 5(c) focuses on realizing the desirable system state of having "no gas faults inside the building." Scenarios relevant to this concern are as follows:

1. A gas pipe in a building is broken, **and** an electric arc from damaged electrical wiring is present near the released gas to ignite it promptly.

2. A hot water heater is overturned by the earthquake motions resulting in a rupture of the gas supply piping, **and** the released gas is ignited by the pilot light of the heater.
3. A gas pipe in a building is broken because the structure deformed so much that pipe could not remain undamaged **and** the ignition of the released gas is delayed until a mixture of gas and air has been created. This scenario can lead to an explosion.
4. Cooking oils and other kitchen fuels are released during the earthquake, **and** in the presence of either electrical- or gas-based cooking equipment these fuels are ignited.

While not identified as part of the literature review, the following scenario was also identified through the analysis.

5. A gas valve that had been open prior to the earthquake (e.g., on a range top) and then was not shut off at the time of restoration of gas service **and** an ignition source, such as a light switch, ignites a fire or an explosion.

The first three scenarios all require the existence of some type of fault involving the distribution of gas **inside** the building. This problem is addressed in the general model, Figure 5(c), where the top desirable systems state is "no gas faults inside the building." On this diagram, increased ground shaking is shown as increasing the likelihood of the scenario state "breaks or leaks in building system." Should such faults exist, then the only viable approach is to shut the supply of gas to the building, which can be accomplished in two ways, either manually or with an automatic shutoff valve that responds to an abnormal release of natural gas. (The role of seismic shutoff valves is discussed below because their activation is not instigated by a fault *per se*) (See Fig. 5(c).

While the general model shows the dynamic relationships between system states, it does not clearly describe the means by which desirable system states are achieved. Goal decompositions are better suited to this purpose. Two such goal decompositions are provided: one covers "the prevention of breaks or leads inside the building," the other covers "building supply shutoff manually."

The shutoff of the gas supply is examined in the goal decomposition model in Figure 4(c). The gas supply can be shut off by the utility, the customer, a neighbor or concerned other person. Regardless of who shuts off the gas supply, all of the following conditions must apply: someone must be available and that person must know how and where to shutoff the gas supply and he/she must have an appropriate tool, typically a wrench. Importantly, the person must be motivated, a condition that could result from the smell of gas or from a perception of risk resulting from the earthquake. The first motivating condition is always desirable; people should always shut off the supply if they detect any smell of gas or identify a risk such as structural damage to the building. Utilities generally recommend that customers not shut off gas supplies if no risk is present because it can delay restoration of gas service. The basis for this recommendation is that safety risks are created by extensive customer outages. These include increased fire risks due to improper use of open fires for cooking and heating, unsafe procedures used to re-light appliance pilot lights by untrained personnel, and lack of checking for gas leaks or damage to gas appliance vents prior to re-lighting pilot lights. The issue is whether customers or other concerned people can reliably detect leaks and shut off gas supplies before hazardous conditions develop.

The problem of preventing a line break at a building is covered in the goal decomposition model shown in Figure 4(d). This desirable system state can be accomplished by either preventing the structural failures that sever gas lines or by preventing breaks at appliances. The first issue is limited to older structures that either have poor shear strength on lower floors or are not secured to a proper foundation. Due to code requirements enforced in recent years, these problems are likely to be limited to older buildings even in the most severe earthquakes, except when earthquake-caused ground failure causes damage to the gas distribution system in the street. The structural vulnerability of a building and the selection of possible structural retrofits of older buildings are within the control of the building owner, but there is little progress in that area in most of California.

The problem of gas line breaks at appliances has received a great deal of attention in recent years. Two strategies are advocated: preventing movement of the appliance (e.g. strapping water heaters) and using flexible connectors. When used together, they largely ensure the realization of this desirable system state. Even when either system is used by itself, especially preventing the movement of appliances, there is a significant reduction in risk.

Returning to the influence diagram model, of Figure 5(c), the desirable system state "an opened gas appliance valve has been closed" addresses scenario 5 above. This is one of two system states, along with "building supply shutoff," either of which can prevent gas faults inside a building. The related sequence of system states is most likely encountered in connection with a stove. A building occupant would be cooking on the stovetop when the earthquake occurs and service is interrupted. Later, when service is restored the open valve leaks gas into the building.

Figure 5(a) of the general influence diagram model illustrates the service restoration problem. In order to realize the desirable system state "no hazardous amount of gas leaks into building," either of two system states must be realized: (1) there must be "no faults in the building system;" or (2) "a hazardous amount of pressurized gas must not be available." A utility's restoration program is based on eliminating faults from the system before restoring building service. Before service is restored to an area, all shutoff valves to buildings are closed. Then, trained technicians or plumbers are recommended to restore service and re-ignite pilots lights after checking for leaks. The process becomes problematic when building occupants or other persons restore service. Customers, building managers, owners, or whoever else are increasingly likely to restore service after having waited for days or weeks without being visited by a qualified technician, a situation that is likely to occur following a large earthquake. The hazard involved in customer restoration depends on the likelihood of easy detection of faults, as discussed earlier.

Alternative Means to Stop Delivery of Gas

As noted previously, many of the older **R-1** occupancies are not expected to respond well to a high-intensity earthquake. If the MMI reaches VIII or IX in such older urban areas, there is a high probability that people will be trapped in one or more older buildings due to partial collapse of structural elements as well as damage to non-structural elements such as doors and stairways. After the earthquake, it is most probable that the gas distribution system* will continue to supply gas to these buildings, but the buildings' internal gas pipe systems will likely have been damaged as these old structures respond to the earthquake. The gas pipe systems in any building, but particularly in the older buildings, are not generally designed to be earthquake-resistant. Architects roughly plan the gas pipe systems in most buildings, and then they are installed by plumbers or pipe-fitters who have little or no training in earthquake resistant features. In general, the pipe material is of a low-grade steel with threaded connectors that do not behave in a ductile fashion. It is possible to improve the design of a pipe system within a building that will respond properly in an earthquake by using corrugated stainless steel tubing (CSST).

Figure 5(d) of the general model shows, in part, the relationship between earthquake performance of gas distribution lines and earthquake-related fires. The top-level system state is "hazardous amount of pressurized gas not available." The system state will exist if any of the following three system states are found:

1. The distribution system does not contain a hazardous amount of gas; or
2. The gas supply to the building has been shut off; or
3. The gas supply has been restored, but the service to the building has not been turned back on.

A distribution system will not contain a hazardous quantity of gas if either of the following system states is found: (1) the gas pipeline breaks and vents the gas; (2) intentionally disrupting gas supply to a small area that has suffered extensive damage, which can be accomplished by using distribution pipeline shut-off valves, or by shutting off the flow of gas by squeezing the main where a valve may not exist **. There are other means to reduce the amount of gas leakage into a building, as discussed below in the section on "Automatic Seismic Shutoff Valves versus Excess Flow Valves." The second means for preventing a hazardous amount of gas, i.e., shutting off the supply to the building, can be achieved by either of two approaches: (1) a shutoff valve can activate; or (2) the service can be shut off manually. Both approaches can cost the customers considerable inconvenience while they wait for an authorized person to restore their service. The third means for preventing a hazardous amount of gas is accomplished during the restoration phase. In this instance, the gas distribution system has been restored, but the service to the building has not been turned back on, delaying restoration of the natural gas service++ until the building has been fully checked out.

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* This is particularly true where the gas distribution system has been upgraded to give better seismic performance.

** There are pre-defined shut off areas in a utility's system, (e.g, the Marina District in San Francisco.

++ The gas service to a given unit in a multifamily building means that there is natural gas available beyond the meter for that unit.

Another characteristic that is relevant to this analysis is whether single or multiple gas meters are used to measure the use of natural gas in the building. This characteristic is important for the following reasons: the seismic shutoff valve is often required to be on the customer's side of the meter. In an apartment house or condominium building with 40 units there would have to be 40 shutoff valves. Thus the cost and organizational complexities of installing automatic seismic shut-off valves would be greater in multi-metered buildings. For example, owners, managers, and residents may have different interests in whether shutoff valves should be installed. Moreover, in multi-metered buildings there is a greater likelihood of false trips due to the location and the number of required shutoff valves. This is also true for older valve designs where there is the possibility of false trips. Another approach would be to install excess-flow valves on the gas line to each apartment or condominium so that if a gas line breaks the gas to that particular customer is shutoff. It should be recognized that the excess-flow valve would not be sensitive enough to shutoff the gas flow if it is below the individual valve's designed trip characteristics (e.g. partial break). It would then simply function as normal usage. A third alternative would be to install an excess-flow valve on the service line coming to the building from the street main. These valves are typically installed to prevent gas leakage due to pipe damage during street excavations, but they can also protect against major high-pressure gas leakage inside a building due to severe structural damage.

Automatic Seismic Shutoff Valves versus Excess Flow Valves

There are two common ways to automatically stop the flow of gas to a leaking or broken gas pipe following an earthquake. One is to install an automatic seismic actuated shutoff valve that is designed to close under specific dynamic conditions, and the second is to install an excess flow valve that is designed to close under abnormally high flow conditions*. The use of each of these devices has certain advantages as well as certain disadvantages that will be reviewed here.

Earthquake-actuated automatic seismic shutoff valves used in California currently comply with ANSI Standard Z21.70-1981. At the time of this report, an updated standard prepared by the American Society of Civil Engineers (ASCE), Standard ASCE 25-97 *Earthquake-Actuated Automatic Gas Shutoff Devices*[67] updates the ANSI standard, and is being considered for use in the State of California. The abstract on the inside cover of the ASCE standard summarizes its purpose and limitations.

> This standard provides minimum functionality requirements for earthquake-actuated automatic gas shutoff devices and systems meant to include mechanical devices consisting of a sensing means and a means to shut off the flow of gaseous fuels. It basically applies to single-family or multi-family structures of three stories or less. The seismic performance established by this Standard are based upon data from recent earthquakes, primarily in Southern California.

The range of motions defining the response of devices tested to this standard are shown in Figure 6. For actuation the standard specifies that: "the sensing means of the device shall

* Other ways also exist such as methane sensors that trigger valves when methane is detected. The methods can be accomplished any time a break in the gas line is detected, not just after an earthquake.

actuate the shutoff means within 5 seconds when subjected to horizontal sinusoidal oscillation having

1. a peak acceleration of 0.70 g (6.87 m/s^2) with a period of 0.13 seconds,
2. a peak acceleration of 0 40 g (3.92 m/s^2) with a period of 0.20 seconds
3. a peak acceleration of 0.30 g (2.94 m/s^2) with a period of 0.40 seconds and
4. a peak acceleration of 0.25 g.(2.45m/s^2) with a period of 1.00 seconds

These conditions shall be met for horizontal axes of the sensing means."

Of perhaps more importance, the standard specifies the requirements for non-actuation to be that: "the sensing means of the device shall not actuate the shutoff means within when subjected for 5 seconds to sinusoidal oscillation having

1. a peak acceleration of 0.40 g (3.92 m/s^2) with a period of 0.10 seconds,
2. a peak açceleration of 0.20 g (1.96 m/s^2) with a period of 0.20 seconds,
3. a peak acceleration of 015 g (1.47 m/s^2) with a period of 0.40 seconds, and
4. a peak acceleration of 0.10 g (0.98 m/s^2) with a period of 1.00 seconds

These conditions shall be met for both horizontal and vertical axes of the sensing means."

A short history of the development of the standard is given in the preamble of the standard. Draft standards were developed in the 1970s, and an ANSI Standard was approved in 1981. This standard was not considered adequate, and in 1991 the ASCE Technical Council on Lifeline Earthquake Engineering formed a Pre-standards Committee to revise the shutoff valve standard. A full Standards Committee was formed in 1992, but their work did not really begin in earnest until after the Northridge earthquake of January 17, 1994. The result of the committee's initial study was a recommendation for the initiation of a research project that should focus on two key areas:

1. The dynamic testing of current devices in order to quantify performance characteristics, and
2. An in-depth examination of the Northridge earthquake data on ground motions, structural damage, fire initiation, and actuation of existing shutoff devices.

A research project was initiated in March 1995, and completed in November 1995[68]. The performance response characteristics of the devices on the market at that time were evaluated for both discrete dynamic loads as well as complex motions such as simulated earthquakes. The committee set the levels of actuation in the standard using these research findings. In the "commentary" section of the standard the committee writes:

> "Based on the Northridge earthquake, the Standard requirements are judged to be conservative by 30% to 50% in the critical frequency range of 2.5 Hz to 5 Hz."

The reliance on the Northridge earthquake may be one of the most important aspects of this standard. There is a list of seven assumptions given in the commentary section of the standard:

1. "The identified limits are based on encompassing more than 95% of all gas-related fires (in the Northridge earthquake).
2. The typical structural configuration is considered to be a wood-frame, single-family or multi-family structure of three stories or less.
3. The atypical structural or gas installation configuration may require an engineered system, suitable for the type of facility and end-user's risk tolerance.
4. The dynamic loads on gas appliances caused by the earthquake can be related to free-field ground motions. Global response of gas-fired equipment located at ground level (sliding or overturning) was considered in establishing actuation limits.
5. The structure and the gas appliance configurations are consistent with an assumed damping ratio of 5% or greater.
6. Within the actuation limits, it is assumed that leaks in gas-fired equipment or the houselines do not occur. Houseline damage is generally associated with significant structural damage, which is not expected within the actuation ranges.
7. The post-Northridge earthquake research activity did not investigate the complex relationship among observed structural damage, peak spectral acceleration levels, underlying soil and geologic conditions, or ages of the structures.

The "Appendix" of the standard contains several sections devoted to various topics:

Issues and Considerations for Public Officials Formulating Regulations for Mandated Installation of Earthquake-Actuated Automatic Gas Shutoff Devices

Reducing Risk of Post-Earthquake Conflagration

Structural Performance Issues

Interruption of Gas Service

Cost Versus Benefit Considerations

Monitoring Performance

Although the appendices of a U. S. Standard are not considered a part of the required language of a standard, they can be of considerable use for a critical review of the document. For instance, in the Section on *Cost versus Benefit Considerations* there is a statement "Consideration should be given to mandating installation of appliance restraints. This action alone is estimated to accomplish 80% of the risk reduction provided by earthquake-actuated gas shutoff devices based upon historical fire data and analytical investigations." This viewpoint is largely a product of using the Northridge Earthquake as a principle source of information. A statement is made in a preceding paragraph that: "An overwhelming majority of post-earthquake, gas-related fire incidents are related to shifting or overturning of gas appliances, especially water heaters." The ASCE Standard thus provides a wide range of information about the use and operation of seismic shutoff valves.

At the time of this report, the State of California is considering adoption of American Gas Association (AGA) Requirements for Excess Flow Valves No. 3-92, dated January 30, 1996, as the applicable standard to be used for certification of excess flow valves. This standard applies to devices not in excess of 2-inch size and operating pressure not in excess of 5 psi.

There are several manufacturers of low-pressure excess flow valve for both natural gas and propane. The excess flow valves operate at pressures as low as 0.25 psi and even lower. They close when the flow of gas exceeds a specific design limit, usually at a point above the maximum flow calculated from the rated capacities of all of the connected appliances. The valve is installed on the customers' houseline. Then, when an earthquake occurs, the valve would close if a gas leak resulted that was greater than the factory-set shutoff flow value. There is the possibility that a partial break in the gas line would result in a gas flow lower than the excess limit set and the valve will not trigger closed.

Utilities install excess gas flow valves in accordance with DOT guidelines 192.381 and 192.383. They are installed on single-family residences (1 meter) only. They are not installed on branch services, commercial buildings, or multi-family buildings. Utilities have the option to voluntarily install the excess gas flow valves or take the customer notification approach discussed in 192.383. There are two industry standards that specify the manufacturing requirements for excess gas flow valves that operate at 10 psi and above. One was developed by the Manufacturers Standardization Society (MSS) for the Valve and Fittings Industry and is called Standard Practice for Excess Flow Valves for Natural Gas Service (#SP-115). The other is ASTM F-1802 and is called the Standard Test Method for Performance Testing of Excess Flow Valves. These standards are for the manufacture and performance of the excess gas flow valves, not for their installation. [Reference for entire paragraph][69]

DOT 192.381 states that excess gas flow valves do not need to be installed if the main pressure is less than 10 psi. Thus in practice excess gas flow valves are not designed to operate at pressures less than 10 psi. Different flow models are designed to activate at different capacities. As the flow in the main pressure increases, the flow required to activate the excess gas flow valve also increases. At the same main pressure, the flow to activate the excess gas flow valve is higher when the service is 6' in length than when it is 100' in length. These high pressure excess gas flow valves are not designed to activate at low flows and will not shutoff if there is a small leak less than the designed activation flow of the excess gas flow valve. Activation will occur if the service tubing is severed. [Reference for entire paragraph][70]

The advantages and disadvantages of each of these types of control valves depend on many factors. A partial listing is as follows:

ADVANTAGES & DISADVANTAGES OF AUTOMATIC SEISMIC SHUTOFF VALVES

Advantages:

1. The valves operate automatically when they detect motions above their designed threshold. Their performance is governed by standards as they are adopted by regulatory agencies.
2. Previously installed valves have a proven record in protection of **R-3** occupancies.
3. Activation completely eliminates leakage of gas beyond the valve.
4. Their installation is site specific, which permits only those structures that are vulnerable to damage during an earthquake to be protected, without incurring the cost of installation on structures that are otherwise protected.

Disadvantages:

1. Standard ASCE 25-97 *Earthquake-Actuated Automatic Gas Shutoff Devices* is in place and gives performance standards for the devices as well as guidance in their installation, but it is not being used by the State of California. Valves currently approved by the State of California only have to meet the requirements of ANSI Standard Z21.70-1981. This could change soon pending adoption by the State of California.
2. The standard ASCE 25-97 applies to single-family or multi-family structures of three stories or less, and does not explicitly address all R-1 occupancies.
3. Some valves are prone to being tripped by accidental impacts or vibrations from normal (non-seismic) activities.
4. Many valve models currently installed or available, activate closed solely on motion alone, and do not have the ability to determine if a hazardous condition actually exists, thus causing unnecessary interruption of customer gas service.
5. Widespread valve installations can result in the shutting off of gas service at a time (i.e., post-earthquake) when utility and community resources are in high demand for leak repairs, safety checks, and service restorations, and thus can create delays in the restoration of service.
6. Aftershocks could cause devices to activate after has service has been restored.
7. The major problem in R-3 occupancies is the overturned hot water heater, which can be effectively addressed by less expensive means than the seismic valve.
8. Many models of valves that are available can be manually reset by unqualified personnel, without requiring that checking be done to assure that a hazardous condition does not exist.
9. Extensive structural damage may render a device ineffective due to damage to the gas piping system or the device itself. The device will not provide any protection from damage upstream of the device.

ADVANTAGES & DISADVANTAGES OF EXCESS FLOW SHUTOFF VALVES

Advantages:

1. The valve responds to the presence of a hazard when it operates automatically after detecting a gas flow rate above its designed threshold.
2. This valve only shuts off the gas if there is a large leak on the piping system. Because the probability of activation is far less than with the seismic valves, much of the potential delay in restoration of service is eliminated.
3. There is a by-pass feature that causes the valve to automatically reset itself when the gas leak is repaired.
4. Their installation is site specific, which permits only those structures that are vulnerable to damage during an earthquake to be protected, without incurring the cost of installation on structures that are otherwise protected.

Disadvantages:

1. The valve activates only when a catastrophic break in the gas line occurs, there can still be leak(s) in the system that are below the set-point of the valve, resulting in gas flow not being stopped.
2. Available valves have limits in their designed operating conditions, and may not be available for some installations.
3. The major problem in R-3 occupancies is the overturned hot water heater, which can be solved by less expensive means than the excess flow valve.
4. Extensive structural damage may render a device ineffective due to damage to the gas piping system or the device itself. The device will not provide any protection from damage upstream of the device.

It appears that the automatic seismic shutoff valves that conform to the ASCE 25-97 standard are designed to activate prior to the overturning of an un-reinforced hot water heater, which we estimate to occur at about MMI VII. However, automatic seismic shutoff valves that conform to the ASCE 25-97 standard are tested at no more than 0.5 psi pressure, and thus they are not designed to be attached to high-pressure gas distribution systems. Additionally, these valves are not designed to protect R-1 occupancies. High-pressure automatic seismic shutoff valves exist, but there is no general standard, such as ASCE No. 25-97, to provide a basis for their performance. Such seismic shutoff valves that were qualified for R-1 occupancies could be an effective solution to the scenario with people trapped in a partially collapsed building, as discussed above. The dynamic setting of the device would have to be chosen for activation before the MMI or PGA that would substantially damage the specific existing R-1 building. This may correspond to MMI VIII or even IX. If the seismic shutoff valves were installed on the customers' side of the meter, effective performance would depend on the response of the devices installed at the building. Seismic valves installed on a manifold system with 20 or more meters may have a different seismic response than the simple valve tested and described in ASCE 25-97. The use of seismic valves intended for R-3 occupancies might not be at all appropriate for R-1 occupancies where multiple meters dictate the installation of multiple seismic shutoff valves.

The choice of low-pressure excess flow-valves could be an appropriate alternative in those situations where the shutoff valve is on the customers' side of the gas meters. The major disadvantage of this device is its inability to detect a partial loss of integrity in the gas line that would cause a leak below the shutoff setting of the valve. A very small leak could probably be tolerated without substantial risk of fire or explosion, but a leak comparable to the full BTU/hr rating of a cooking range is probably dangerous.

Conflagration Issues

In the Northridge earthquake there were a number of fires in one and two family buildings (R-3 occupancies), and particularly in trailer homes, but there were no reported deaths in these fires. There was, of course, significant property damage in these fires, but compared with the huge financial loss in that earthquake as a whole, the fire losses were insignificant. The real danger for significant property loss lies in the possibility of a conflagration like the one that occurred in the 1906 earthquake in San Francisco. The usual construction of R-3 buildings in the United States, and particularly in California, has a spacing of 6 ft (1.83 m) or more between buildings[71], and this spacing slows down the fire spread between structures unless there are significant winds and the humidity is low. In his discussion of the Northridge earthquake, Scawthorn[72] mentioned the 1991 East Bay Hills Fire as the prototype of a future post-earthquake fire, but from a practical stochastic viewpoint, the combination of a major earthquake and dry windy conditions is a very rare event. There are approximately 5 "fire danger days" per year in the San Francisco Bay Area when the hot dry wind blows from the east[73]. The more normal winds are cool westerly winds that carry the moisture from the Pacific Ocean. These winds do not spread fires as easily as the easterly winds. This is based on fire science that maintains that fire spread depends on "flying brands" to cause "spot fires" to start ahead of the main fire front, and the moist cool maritime air quenches these small air borne brands. The occurrence of hot dry winds in Southern California (Santa Ana conditions) is more frequent than in Northern California. Other steps are being taken in California to prevent the spread of fire between houses. Roofing materials now have to be fire retardant, and older wooden shake roofs cannot be replaced without being up-graded to a fire retardant system. Highly combustible plants are being eliminated between buildings, and the fire service has taken many steps to prevent the kind of fire that occurred in the East Bay Hills in 1991. All of this leads us to conclude that the current stock of R-3 buildings in California does not pose a significant life safety risk for post earthquake fires. The utilities and other governmental agencies could reduce the existent exposure for R-3 property loss by fostering a proper reinforcement of gas hot water heaters and an awareness of earthquake preparations in general.

As discussed previously, it is the older multi-family residential buildings (R-1 occupancies) that are the most likely places for people to be trapped in during the initial hours of a major earthquake and then become the potential victims of a fire before they can be rescued.

The widespread use of wooden construction is another important factor that makes the R-1 fire scenario more dangerous in California. In today's building codes wooden construction (Type V) is restricted to low rise, small area buildings, but in many urban areas much of the R-1 building stock predate these height and area rules. Thus one finds 6 to 10 story apartment houses of a mixed construction of wood, masonry, and concrete. Many of these structures are not designed to withstand the level of seismic shaking that a modern gas system can handle with ease. In addition, many of these buildings have internal gas piping that will fracture as the structure deforms, increasing the likelihood of fire. The wooden buildings will be extremely vulnerable to rapid fire spread since much of the passive fire protection will have been compromised by the earthquake damage.

Either seismic shutoff valves or a system of excess flow valves could be installed in these buildings to reduce the risk of the R-1 fire scenario. In time this risk will go away as these older buildings are replaced by modern construction, but today the potential exists for major post-earthquake life loss.

Electrical Ignition Following Earthquakes

As mentioned in the description of the Kobe earthquake, Sekizawa[74] found that a number of fires started one or two hours after the Kobe earthquake when the electric power was restored to damaged structures. As discussed in conjunction with gas fires, the most dangerous post-earthquake scenarios are in buildings that are heavily damaged and in which people are trapped.

The electrical system of a building already has a circuit breaker or fuses installed to prevent excess current flow, but there are certain damage conditions that can lead to a fire without activating these protection devices. There are also electrically powered appliances such as portable space heaters or high-intensity lights that can cause a fire if they come into contact with potential fuel sources.

Figure 5(b) of the general influence diagram model explores the relationships associated with the top desirable system state "no ignition source present." To realize this state, two system states must be true: (1) "other ignition sources (have been) eliminated;" and, (2) there is "no electrical service ignition source."

The elimination of other ignition sources is a scenario (negative) system state over which the electric utility service has no control. An important example is the increased use of telephone systems that are powered independently of the electrical system and that may remain operational even when the electrical power distribution system has been interrupted. Other possible sources of ignition can include battery-powered devices, static electrical charges, and the use of tools during rescue operations. The conclusion is that it is impossible to eliminate all potential sources of ignition by electricity. Nonetheless, the energized electrical distribution lines are the most likely electrical ignition sources following an earthquake.

Two system states are associated with the desirable system state of "no electrical service ignition source." One of these is the scenario (negative) state of "hazardous electrical service short circuits or ground faults," the elimination of which is beyond the control of electric utilities. Adequate protection against short circuits and ground faults is a function of having a properly designed and maintained building electrical system. Since this scenario state cannot be eliminated, the removal of electrical service to the building is the only fully reliable means to ensure that there are no sources of electrical service ignition.

Electrical service may not be intact for either of two reasons: (1) the earthquake disrupted electrical distribution and it has not been restored (whether intentionally or not); or (2) electrical service is cut off at the service switch or breaker/fuse box to the building. Removal of electrical service is a goal conflict state since it will increase customer discomfort and losses. Therefore, the intentional disruption of electrical service needs to be applied in accordance with the associated hazard. Nonetheless, the delaying of electrical service restoration is an important strategy for reducing ignitions where widespread building damage is evident.

The second approach, when electrical service is intentionally cut off from a building, is an important strategy where: (1) particular buildings with significant damage can be identified, especially those buildings that might contain trapped occupants; and, (2) either electrical service was not disrupted in the first place, or there is not enough damage to justify further delays in restoration of electrical service. In these instances, it is advisable to cut off electrical service to individual buildings to ensure that there will be no possibility of electrical service-related fire ignitions in the cut-off buildings after service has been restored to a geographical area.

There are strong parallels between the discussion of natural gas systems and electrical systems. We do not believe that the one and two family buildings (R-3 occupancies) pose a significant post-earthquake fire problem for essentially the same reasons given for natural gas systems. It is the older multi-family residential buildings (R-1 occupancies), we believe, that are the most likely places for people to be trapped in during the initial hours of a major earthquake and become the potential victims of a fire before they can be rescued. The current electrical system is not capable of continued operation with a very intense earthquake, so except for the short time of the initial shocks of the earthquake, there are few ignitions caused by electrical shorts and arcs. Routing the natural gas and electric service in separate spaces in the building could prevent some of these ignitions. This practice is used in commercial aircraft because it was found that in accidents the close spacing of fuel and electrical lines ignited fires. In subsequent accidents that were essentially of a similar nature, there was no fire because the fuel and electrical lines had been separated[75].

The potential problems with electrical ignitions occur during the restoration of power. Before power is restored to an area, the electric utility needs to have a positive way to know about collapsed or damaged buildings that still have people trapped inside them. Plans are in place to coordinate this kind of effort, but the training of fire fighters and other emergency responders need to be included in this planning. The information chain starts with the people in the field who identify the buildings with trapped people. The emergency responders need to be made aware that the power utility might try to restore power as soon as possible after the earthquake, and that it is their responsibility to send communication about the current situation. It might also be effective if the emergency responders could be made to be responsible for disconnecting the electrical service to the building. If that is not practical, then they should contact the utility to have their service personnel come out to disconnect the service. This could be part of the information exchange between the emergency responders at the scene and the utility command center.

CONCLUSIONS

A survey of the literature on the fire aspects of eleven large twentieth century earthquake events has been conducted. They are as follows:

San Francisco, California	1906
Kanto (Tokyo) , Japan	1923
Hawkes Bay, New Zealand	1931
Long Beach, California	1933
Managua, Nicaragua	1972
Morgan Hill, California	1984
Mexico City, Mexico	1985
Whittier Narrows, Los Angeles, California	1987
Loma Prieta, California	1989
Northridge, California	1994

Hyogo-ken Nanbu (Kobe), Japan 1995

A review of the literature on the fire aspects of these earthquakes yields a list of ignition scenarios in which either the gas or electric service played a role in the ignition of the first fuel in the fire:

1. A gas pipe in a building is broken, **and** an electric arc from damaged electrical wiring was present near the released gas to ignite it promptly.
2. Bottles and/or open cans of flammable liquids are thrown to the floor by the earthquake, **and** an open gas flame or an electric arc is present to ignite the vapors from the spilled liquid
3. A hot water heater is overturned resulting in a rupture of the gas supply piping, **and** the released gas is ignited by the pilot light of the heater
4. A gas pipe in a building is broken because the structure deformed so much that pipe could not remain undamaged **and** the ignition of the released gas is delayed until a mixture of gas and air has been created. This scenario can lead to an explosion.
5. Cooking oils and other kitchen fuels are spilled or released during the earthquake, **and** either electrical- or gas-based cooking equipment ignites these fuels
6. While the electrical service to a structure is interrupted by the initial earthquake event, the earthquake motions displace or damage an electric-powered device and put it into contact with some quantity of fuel. Then when the electric power is restored to the building, this displaced device causes the ignition of the exposed fuel.
7. A person ignites a fire by such means as arson or turning on a light switch with natural gas present.

This report focuses on two scenarios that can occur in residential structures. The first is in one and two family housing (R-3 occupancies), and the second scenario is in older multi-family residential buildings (R-1 occupancies). Here are our conclusions:

1. An analysis of many factors has lead us to conclude that the current stock of R-3 buildings in California do not pose a significant life safety risk for post earthquake fires. There is some exposure for R-3 property loss that utilities and other governmental agencies could reduce by fostering the proper reinforcement of gas hot water heaters and an awareness of earthquake preparations in general.
2. The most dangerous post-earthquake fire threat appears to be the R-1 fire scenario where people are trapped in multifamily buildings which have partially collapsed and in which gas pipes are broken with gas leaking into the structure. The rescue of these people will be very difficult, and the potential for fire is very great. Either seismic shutoff valves or a system of excess flow valves could be installed in these buildings to reduce the risk of the R-1 fire scenario. In time this risk will go away as these older buildings are replaced by modern construction, but today the potential exists for major post-earthquake life loss.

A review of a systems approach to the problem leads to the important conclusion that in the post-earthquake environment attention must be paid to **Ignition Prevention** rather than **Fire Management**. Reducing the potential dangers of the R-1 fire scenario should be one of the top priorities in earthquake preparations in California. It will take a concerted effort of government, private property owners, and the utilities to find solutions to this problem. The rational and central emphasis of this effort will be to prevent **Ignition of Fire** by eliminating the leaking of natural gas in the expected partial collapse of older R-1 buildings.

Recommendations for Further Research

The post-earthquake R-1 fire scenario appears to be the most important topic for future research. Here are a few ideas:

1. The models shown in Figures 4 and 5 should be quantified. Expert opinion and some surveys of existing conditions could be used to develop these models. The results of this quantification should lead to an estimate of likelihood and the consequences of this scenario occurring under various potential earthquakes. The emphasis in this quantification should be in the area of the R-1 fire scenario discussed above.
2. Once the models shown in Figures 4 and 5 have been quantified they can be updated by Baysian methods following any earthquake that might occur in areas that are prone to the R-1 fire scenario. Part of this phase of the research should be directed at creating techniques and strategies for the post-earthquake investigation of potential R-1 fire scenarios. This would be important for the Baysian updating of models.
3. It is apparent from the discussion of seismic shut-off valves as well as excess flow valves that there are many problems connected with their application, design and testing. It would be important to have a long-range research program to investigate the whole scope of issues in this area. We recommend a University program since it can serve as a "third-party" testing agency to evaluate and certify performance under a Service-to-Industry program at the same time that it is developing the test methods and performance criteria. In addition, the University has a broad staff of professors in many important areas of expertise, and technicians and students with the necessary backgrounds. For instance, within the PEER family of institutions there is an impressive array of people to carry out the proposed program.

The three research topics presented here could be divided into many subparts, but it would be important to involve the potential governmental and private sector individuals who would be the users of the research findings. The next phase of the research should involve the California Office of Emergency Service (OES) and the California State Fire Marshall's (CFM) office. In the private sector there should be liaison with utilities as well as R-1 building owners and managers. It will be important at some point to involve the city building and fire departments, although initially the OES and CFM represent their interests.

REFERENCES

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[1] Williamson, R. B., *Coupling Deterministic and Stochastic Modeling to Unwanted Fire*, **Fire Safety Journal, 3**, 4, 243-259, (1981).

[2] Ramachandran, G. *Stochastic Models of Fire Growth.* In the **SFPE Handbook of Fire Protection Engineering**, 2nd Edition, Quincy, MA: National Fire Protection Association (1995).

[3] Beck, V. R., *A Cost-Effective Decision-Making Model for Building Fire Safety and Protection*, **Fire Safety Journal, 12**, 121-138 (1987).

[4] Ling, T. L., and Williamson, R. B., *Modeling of Fire Spread through Probabilistic Networks*, **Fire Safety Journal, 9**, 287-300 (1985).

[5] Groner, N. E., and Williamson, R. B., *Scenario-Based Goal Decomposition: A Method for Implementing Performance-Based Fire Safety Analysis*, presented at the 2nd International Conference on Fire Research and Engineering, National Institute of Standards and Technology, Gaithersburg, MD, August 10-15, 1997.

[6] Ibid

[7] Botting , R., *The Impact of Post-earthquake Fire on the Urban Environment*, Fire Engineering Research Report 98/1, Christchurch, New Zealand, University of Canterbury, School of Engineering, p 173, (1998).

[8] Williamson, R. B., and Dembsey, N. A., *Advances in Assessment Methods for Fire Safety*, **Fire Safety Journal, 20**, 15-38, (1993).

[9] Scawthorn, C., *Simulation Modeling of Fire Following Earthquake, Proceedings of the Third U. S. National Conference on Earthquake Engineering, Charleston, SC, 1986,* volume III, El Cerrito, CA, Earthquake Engineering Research Institute, (1986).

[10] Ibid. p. 5

[11] *U.S.-Japan Workshop on Urban Earthquake Hazards Reduction, Stanford University, July 29-August 1, 1984, Proceedings,* Berkeley, CA, Earthquake Engineering Research Institute, EERI Publication No. 85-03, p. 5, (1985).

[12] Steinbrugge, K. V., *Earthquakes, Volcanos, and Tsunamis – an Anatomy of Hazards*, SKANDIA America Group, (1982).

[13] Scawthorn, C., Blackburn, F.T. , and Seagraves, D.. W., *Earthquakes, Fires & Urban Areas – All the Ingredients for a Disaster*, **Fire Safety Journal, 82**, 4, 20-30, (1988).

[14] Steinbrugge, K. V., *Earthquakes, Volcanos, and Tsunamis – an Anatomy of Hazards,* SKANDIA America Group, (1982).

[15] Ibid., p. 94.

[16] Ibid., p. 95.

[17] Botting , R., *The Impact of Post-earthquake Fire on the Urban Environment*, Fire Engineering Research Report 98/1, Christchurch, New Zealand, University of Canterbury, School of Engineering, p. 173, (1998)

[18] Ibid., p. 177.

[19] Ibid., p. 181.

[20] Ibid., p. 181-182.

[21] Earthquake Engineering Research Institute, *Managua, Nicaragua Earthquake of December 23, 1972, Conference Proceedings*, vol. II, Berkeley, CA, (1973).

[22] Botting , R., *The Impact of Post-earthquake Fire on the Urban Environment*, Fire Engineering Research Report 98/1, Christchurch, New Zealand, University of Canterbury, School of Engineering, p. 193, (1998).

[23] Earthquake Engineering Research Institute, *Managua, Nicaragua Earthquake of December 23, 1972, Conference Proceedings*, vol. II, Berkeley, CA, (1973).

[24] Schiff, A. J., *Investigation of Lifelines*, **Earthquake Spectra, 1**, 3, p. 623, (1985)

[25] Scawthorn, C., Bureau, G., Jessup, C., and Delgado, R., *The Morgan Hill Earthquake of April 24, 1984 – Fire Related Aspects*, **Earthquake Spectra, 1**, 3, , p. 678, (1985).

[26] Scawthorn, C., *Fire Following Earthquake*, **Fire Engineering**, p.138 (1985).

[27] Scawthorn, C., Bureau, G., Jessup, C., and Delgado, R., *The Morgan Hill Earthquake of April 24, 1984 – Fire Related Aspects*, **Earthquake Spectra, 1**, 3, pp. 675-681, (1985).

[28] Ibid., p. 682.

[29] *The Mexico Earthquake of September 19, 1985*, **Earthquake Spectra, 4**, 3, 1988.

[30] Bolt, B. A. *Earthquakes*, 4th ed., W.H. Freeman, New York, 1999, p. 295.

[31] Botting, R ., *The Impact of Post-earthquake Fire on the Urban Environment*, Fire Engineering Research Report 98/1, Christchurch, New Zealand, University of Canterbury, School of Engineering, p. 201 (1998)

[32] Bertero, V., personal communication, (1998).

[33] *Whittier Narrow Earthquake of October 1, 1987*, **Earthquake Spectra, 9**, 1, (1993).

[34] Smoke, C. H., *A Real Life Practice Run*, **Fire Journal, 82**, 4, p. 29, (1988).

[35] *Whittier Narrow Earthquake of October 1, 1987*, **Earthquake Spectra, 9**, 1, (1993).

[36] Alyasin, M. S., and Bak, D. N. *Investigation of Cause and Effects of Fires Following The Loma Prieta Earthquake,* IIT, Department of Civil Engineering, IIT-CE-92-01, Chicago, Illinois Institute of Technology, 1992, 181 p.

[37] Coleman, R. J., *Fire Department Response During Earthquake Emergency Operations, Firesafety Frontier '94, Proceedings of the Tokyo International Fire Conference*, Tokyo Fire Department, (1994).

[38] Alyasin, M. S., and Bak, D. N. *Investigation of Cause and Effects of Fires Following The Loma Prieta Earthquake,* IIT, Department of Civil Engineering, IIT-CE-92-01, Chicago, Illinois Institute of Technology, 1992, 181 p.

[39] Ibid, pp115-117.

[40] Lew, H. S., ed. *Performance of Structures During the Loma Prieta Earthquake of October 17, 1989,* NIST Special Publication 778, Gaithersburg, MD, National Institute of Standards and Technology, pp. 6-10, (1990).

[41] Chung, R. M., Jason, N. H., Mohraz, B., et al., eds., *Post-earthquake Fire and Lifelines Workshop, Long Beach, California, January 30-31, 1995, Proceedings,* NIST Special

Publication 889, Gaithersburg, MD, National Institute of Standards and Technology, pp. 27-28, (1995).

[42] Scawthorn, C., Cowell, A. D., and Borden, F., *Fire-related Aspects of the Northridge Earthquake*, NIST GCR 98-743, Gaithersburg, MD, National Institute of Standards and Technology, 164 p. (1998).

[43] Ibid., pp. 3-56 to 3-57

[44] Ibid

[45] Ibid, pp. 3-56 to 3-57

[46] Ibid, pp. 3-51 to 3-52

[47] Todd, D., Carino, N., and Chung, R. M, *1994 Northridge Earthquake; Performance of Structures, Lifelines and Fire Protection Systems,* NIST Special Publication, 862, Gaithersburg, MD, National Institute of Standards and Technology, (1994).

[48] Strand, C. L., *Gas Leaks, Gas-related Fires, and Performance of Seismic Gas Shutoff Valves During the Northridge Earthquake,* in **Proceedings of the 4th U.S. Conference, San Francisco, August 10-12, 1995**, (O'Rourke, M. J., ed.), Technical Council on Lifeline Earthquake Engineering, Monograph, No. 6., New York, N.Y., American Society of Civil Engineers, pp. 692-699 (1996).

[49] Scawthorn, C., Cowell, A. D., and Borden, F., *Fire-related Aspects of the Northridge Earthquake*, NIST GCR 98-743, Gaithersburg, MD, National Institute of Standards and Technology, 164 p. (1998).

[50] Strand, C. L., *Gas Leaks, Gas-related Fires, and Performance of Seismic Gas Shutoff Valves During the Northridge Earthquake,* in **Proceedings of the 4th U.S. Conference, San Francisco, August 10-12, 1995**, (O'Rourke, M. J., ed.), Technical Council on Lifeline Earthquake Engineering, Monograph, No. 6., New York, N.Y., American Society of Civil Engineers, p. 698, (1996).

[51] *Proceedings of the Sixth US-Japan Workshop on Earthquake Disaster Prevention of Lifeline Systems, July 1995, Osaka, Japan,* Berkeley, CA, Earthquake Engineering Research Institute (1996).

[52] Chung, R. M., Jason, N. H., Mohraz, B., et al., eds., *Post-earthquake Fire and Lifelines Workshop, Long Beach, California, January 30-31, 1995, Proceedings*, NIST Special Publication 889, Gaithersburg, MD, National Institute of Standards and Technology, pp. 29-33, (1995).

[53] Sekizawa, A., *Post-Earthquake Fires and Performance of Firefighting Activity in the Early Stages in the 1995 Great Hanshin Earthquake* in **Fire Safety Science - Proceedings of the Fifth International Symposium,** (Hasemi, Y, ed.), International Association for Fire Safety Science, p. 972, (1997).

[54] Ibid., p. 973

[55] Chung, R., ed., *The January 7, 1995 Hyogoken-Nanbu (Kobe) Earthquake; Performance of Structures, Lifelines, and Fire Protection Systems,* NIST Special Publication, 901, Gaithersburg, MD, National Institute of Standards and Technology, pp. 497-502, (1996).

[56] Botting , R., The Impact of Post-earthquake Fire on the Urban Environment, Fire Engineering Research Report 98/1, Christchurch, New Zealand, University of

Canterbury, School of Engineering, p. 233, (1998).

[57] Sekizawa, A., *Post-Earthquake Fires and Performance of Firefighting Activity in the Early Stages in the 1995 Great Hanshin Earthquake* in **Fire Safety Science - Proceedings of the Fifth International Symposium,** (Hasemi, Y, ed.), International Association for Fire Safety Science, p. 981, (1997).

[58] International Conference of Building Officials, *1997 Uniform Building* Code, Sec. 310.4 Whittier CA, pp. 1-26 to 1-27, (1997).

[59] Mallick, D. V., and Saud, A. F. B., *Post Earthquake Scenario, Proceedings of the 4th U.S. Conference, San Francisco, August 10-12, 1995,* in Technical Council on Lifeline Earthquake Engineering, Monograph, No. 6., (O'Rourke, M. J., ed.), New York, N. Y., American Society of Civil Engineers, pp. 779-786 (1996).

[60] Scawthorn, C., *Fire Following Earthquake,* in **Fire Safety Science, Proceedings of the First International Symposium** (eds. C. E. Grant, and P. J. Pagni), pp. 971-979, Washington, D.C., Hemisphere Publishing Corporation, (1986).

[61] National Fire Protection Association, *Fire Concepts Tree,* NFPA Standards 550, Quincy, MA, (1983).

[62] Groner, N. E., and Williamson, R. B., *Scenario-Based Goal Decomposition: A Method for Implementing Performance-Based Fire Safety Analysis,* presented at the 2nd International Conference on Fire Research and Engineering, National Institute of Standards and Technology, Gaithersburg, MD, August 10-15, 1997.

[63] Groner, N. E., *A Fire Department Guide to Evaluate Fire Emergency Plans,* presented at a Seminar for the California State Fire Chiefs Association, Oct. 18, 1989, San Luis Obispo, California, Sacramento, CA, Favro, McLaughlin & Associates, (1989).

[64] International Conference of Building Officials, *1997Uniform Building* Code, Sec. 310.4 , Whittier CA, p. 1-26, (1997).

[65] American Society for Testing and Materials, *Annual Book of ASTM Standards,* Vol. 04.07, West Conshohocken, PA, revisions issued annually.

[66] Botting , R., *The Impact of Post-earthquake Fire on the Urban Environment,* Fire Engineering Research Report 98/1, Christchurch, New Zealand, University of Canterbury, School of Engineering, p. 153, (1998). [Source: Cousins et al., *Fire Following Earthquake,* DSIR Physical Sciences, Lower Hutt, New Zealand, (1990)].

[67] American Society of Civil Engineers *Earthquake-actuated Automatic Gas Shutoff Devices,* ASCE Standard 25-97, Reston, VA (1998).

[68] Honegger, D. G., *Automatic Gas Shutoff Device Actuation Requirements Based on Damage in the Jan. 17, 1994 Northridge Earthquake,* a report for ASCE by EQE International, Inc., project 52316.01, San Francisco, CA (1995).

[69] Sullivan, Gene, P. G. & E., private communication, August 1999.

[70] Sullivan, Gene, P. G. & E., private communication, August 1999

[71] International Conference of Building Officials, *1997Uniform Building Code,* Table 5A, and Section 503, Whittier CA, pp. 1-51 & 1-57, (1997).

[72] Scawthorn, C., Cowell, et al. , *Fire-related Aspects of the January 17, 1994 Northridge Earthquake,* in **Proceedings of the 4th U.S. Conference, San Francisco, August 10-12,**

1995, (O'Rourke, M. J., ed.), Technical Council on Lifeline Earthquake Engineering, Monograph, No. 6.' New York, N.Y., American Society of Civil Engineers, p. 688, (1996).

[73] Pagni, P. J., private communication.

[74] Sekizawa, A., *Post-Earthquake Fires and Performance of Firefighting Activity in the Early Stages in the 1995 Great Hanshin Earthquake* in **Fire Safety Science - Proceedings of the Fifth International Symposium,** (Hasemi, Y, ed.), International Association for Fire Safety Science, p. 972, (1997).

[75] Brenneman, J., private communication about the Boeing 727 accidents in Salt Lake City and New York in the late 1960's.